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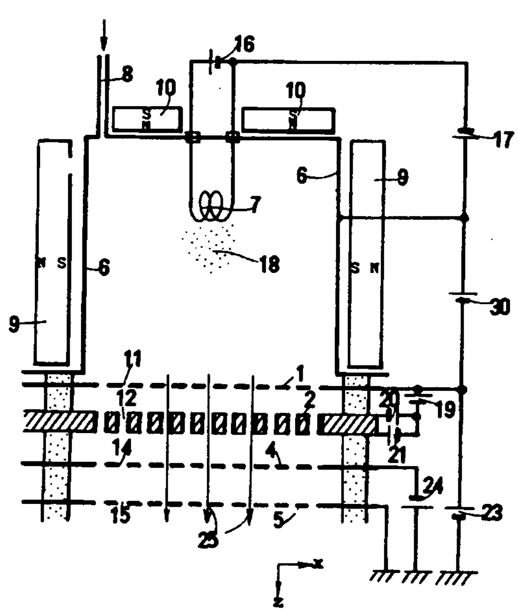
(54) Ion source having a mass separation device.

(57) An ion source (6, 7) for producing wide, large area type ion beams with a mass-separation device. Four, five, six or so electrode plates (1, 2, 4, 5) with ion holes (11, 12, 14, 15) at the same positions are installed at the outlet of the ion source. A second or third one of the electrodes (2) has Wien filters at the ion holes. The Wien filter has permanent magnets (40, 41) and electrodes (42, 43) for producing a magnetic field and an electric field perpendicular to the axial direction of the ion holes. Ion beams which have not been accelerated so fast are separated by mass by the Wien filter. Low kinetic energy of ions alleviates the strength of the magnetic field and the electric field. Wide, large area type ion beams without impurities are obtained.

FIG. 1



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This invention relates to a large area type ion source having a mass separation device. An ion source is a device which converts a gas introduced into a vacuum chamber into plasma and makes ion beams by pulling ions out.

Ion sources have been used for various purposes in various fields of technology, e.g. for doping impurities into semiconductor devices, liquid crystal TFT or solar cells, for etching objects by ion beams, for cutting or polishing by ion sputtering, for depositing thin films by ion beams, for improving the quality of objects or for processing objects on some purpose.

Narrow ion beams with small diameter have also been utilized. In general, narrow ion beams have been used more frequently for measuring properties of objects than for processing or treating objects, because narrow ion beams are inconvenient to process or treat objects with high yield.

In the case of narrow ion beams, it is easy to mount a mass separation device at a point of a passage of ion beams. A mass separation device is a device which bends the paths of ion beams by magnets into curved paths with different curvatures, distinguishes ions by the difference of mass and permits the ions with predetermined mass to pass through the device. Such ion sources that produce narrow ion beams are called here zero-dimension type.

However, if the purpose of an ion source is to process objects, wide ion beams are more convenient than narrow ones, because many more objects can be processed in the same process time. The ion sources that can produce wide ion beams are now called large area type.

In the case of wide ion beams, it is difficult to separate ions by mass. Wide diameter hinders the mass separation of ion beams. Theoretically, big magnets could separate ions by mass effectively even for wide ion beams. Because of high kinetic energy and wide diameter of ion beams, mass separation has hardly been done for large area type ion sources which generate wide ion beams.

In general, ion beams have energy as large as 10 keV to 200 keV at an outlet of an ion source. In the case of large area type ion sources, the diameter of ion beams is wide. Bending these wide, strong ion beams would require a large, strong magnet with strong magnetic flux. The diameter of the poles of the magnet must be far larger than that of ion beams. Furthermore, the magnet must have an arc shape which coincides with the curvature of bent ion beams.

It is uneasy to manufacture such a huge, strong magnet. It is still difficult to mount the big magnet at the outlet of an ion source.

By these reasons, conventional large area type ion sources have rarely been equipped with mass separation device so far.

Large area type ion sources which generate wide beams are used for finishing, processing or improving objects or for doping objects with impurity. It is preferable that the ions bombarding objects are restricted to a certain kind of ions which have a definite mass. However, various kinds of ions are excited in an ion source. Without a mass separation device, undesirable ions are not eliminated. Such undesirable ions also bombard objects, which would bring about some inconvenience. Therefore, large area type ion sources also require a mass separation device.

However, conventional mass separation devices which would bend the passage of ion beams by a big magnet with a pair of wide pole pieces would be unpractical because of the huge size of the magnet. A purpose of this invention is to provide a large area type ion source with a mass separation device without increasing the size of an ion source. Another purpose of the invention is to provide a large area type ion source with a mass separation device which works under weak magnetic field and low electric field.

To achieve the foregoing objects and in accordance with the purpose of the invention, embodiments will be broadly described herein.

This invention proposes an ion source having a mass separation device comprising an ion source chamber having a gas inlet and an outlet and being able to be made vacuum for introducing material gas therein and for exciting the material gas into plasma, a plasma electrode plate with plural holes perforated perpendicularly to a surface mounted at the outlet of the ion source chamber for producing ion beams from the plasma in the ion source chamber, an extraction electrode plate with plural holes corresponding to the holes of the plasma electrode plate mounted next to the plasma electrode plate at the outlet of the ion source chamber for extracting ion beams forward, an acceleration electrode plate with plural holes corresponding to the holes of the extraction electrode plate mounted next to the extraction electrode plate in the outlet of the chamber for accelerating ion beams and a grounded electrode plate with plural holes corresponding to the holes of the acceleration electrode plate mounted next to the acceleration electrode plate in the outlet of the chamber, characterized in that every hole of the extraction electrode plate is equipped with a Wien filter including a pair of electrodes for generating a static electric field perpendicular to an axial direction of the holes and a pair of magnetic poles for generating a static magnetic field perpendicular both to the axial direction and to the direction of electric field and only such ions with a certain mass that have passed through the holes of the extraction electrode plate

can pass through the holes of the next acceleration electrode plate.

A conventional ion source has in general three electrode plates with holes, i.e. a plasma electrode plate, an acceleration electrode plate and a grounded electrode plate. The plasma electrode plate is biased with high voltage being the same as the voltage of the chamber. The acceleration electrode plate is biased with negative low voltage. The grounded electrode plate is grounded.

The present invention adds an extraction electrode plate and Wien filters mounted to the holes of the extraction electrode plate. Thus, a feature of the invention is the Wien filters of the holes for separating ions by their mass by the actions of electric field and magnetic field which are perpendicular each other. The Wien filters will separate ions by their mass. A Wien filter is known as a device for separating ions by mass. However, conventional Wien filter was a single, individual device for mass separation of ion beams with high energy. Such a conventional Wien filter used to be mounted at a passage of ion beams which have passed through the last grounded electrode plate.

However, this invention makes use of many Wien filters installed at all the holes of the extraction electrode plate for mass separation of ion beams with low energy before acceleration.

The holes for ion beam passages of four electrode plates, i.e. plasma electrode plate, extraction electrode plate, acceleration electrode plate and grounded electrode plate are perforated at the same positions of the large area type surfaces of the electrode plates. Therefore, a set of four holes of the four electrode plates are aligned along an axial line perpendicular to the plates, because four electrodes are installed in parallel with each other at the outlet of the ion source chamber. However, each diameter of the holes in a set of the electrode plates is not necessarily equal. Therefore, only the ions which have passed through the holes of the extraction electrode plate toward the axial direction without being bent by the Wien filters of the holes, can pass through a series of holes of the acceleration electrode plate and the grounded electrode plate. On the contrary, the ions which have passed the holes of the extraction electrode plate with being bent by the Wien filters, cannot pass through the succeeding holes of the acceleration electrode plate and the grounded electrode plate, because they collide with the surface either of the acceleration electrode plate or the grounded electrode plate.

Ions pass through the holes of the extraction electrode plate with the same energy which is equal to the potential difference between the voltage of the plasma electrode plate and the voltage of the extraction electrode plate. Since the ions passing through the holes of the extraction electrode plate have the same kinetic energy, only such ions with a certain mass can pass straight through the holes. The ions which have heavier mass than the predetermined mass will be bent to some direction. The ions which have lighter mass than the predetermined mass will be also bent to the other direction by the Wien filters. Such ion beams with heavier mass or lighter mass cannot pass through the holes of the acceleration electrode plate or the grounded electrode plate.

Every Wien filter generates a static electric field E perpendicular to the axial line of the hole and a static magnetic flux B perpendicular both to the axial line (the direction of the ion movement) and to the electric field. The velocity of an ion is denoted by "w".

The ions which pass straight through the holes have the velocity w which satisfies the equation,

$$B w = E \quad (1)$$

The energy of ions at the extraction electrode plate is denoted by qV_0, where q is electric charge and V_0 is the voltage between the plasma electrode plate and the extraction electrode plate. M is mass of the ion. The velocity w of ions is given by

$$w = (2 q V_0 / M)^{1/2} \quad (2)$$

Accordingly, in order to separate such ions having a certain mass M from other ions having other mass, the electric field E and the magnetic flux B should be determined to satisfy Eq.(1) and Eq.(2).

This invention provides Wien filters at the extraction electrode plate where the energy of ions is still low. The low energy of ions allows low electric field E of the Wien filters. Low electric field simplifies the structures of the electrode plates and of the supporting insulators. Such simplified Wien filters are easy to produce.

The Wien filter installed at the holes of the extraction electrode plate consists of permanent magnets buried on both sides of the hole and a pair of electrodes. The magnets generate a static magnetic field perpendicular to the axial direction. The electrodes form a static electric field perpendicular both to the axial direction and the magnetic field.

In general, the kinetic energy qV_0 of ions is less than 1 keV at the extraction electrode plate. The Wien filters mounted at the holes of the extraction electrode plate separate ions whose energy is less than 1 keV. In many cases, the energy is several hundreds of eV. Low magnetic field and low electric filed are available for mass separation of such ions with low energy. The ions will be

accelerated to more than 100 keV by the acceleration electrode plate.

Much stronger electric field and magnetic field would be required for mass-separating the ions with energy of 100 keV by a Wien filter.

The advantage of this invention will be explained. The conventional large area type ion source has no mass separation device. This invention provide a large area type ion source with a mass separation device. The mass separation device prevents impurity ions from being implanted into an object.

Instead of bending wide ion beams as a whole, partial small ion beams passing through a hole are bent independently by a Wien filter installed at the hole. Small magnets and small electrodes are available. The size of a Wien filter is very small because of low electric field, low magnetic field and small diameters of the partial ion beams. However, since this invention makes use of many Wien filters, many magnets and electrodes are required.

This invention proposes a further improvement of an ion source which has five electrode plates instead of four. A separation electrode plate is added between the extraction electrode plate and the acceleration electrode plate. The separation electrode plate has narrower holes than the acceleration electrode plate to raise the resolution of mass separation.

The invention will be more fully understood from the following description given by way of example only with reference to the several figures of the accompanying drawings in which,

Fig.1 is a schematic view of an ion source of an embodiment of this invention.

Fig.2 is an enlarged vertical, sectional view near a series of holes of the electrode plates of Fig.1.

Fig.3 is a plan view of a part of an extraction electrode near a hole.

Fig.4 is a schematic view of an ion source of another embodiment of this invention.

Fig.5 is an enlarge, vertical sectional view near two series of holes of the electrode plates of Fig.4.

Fig.6 is a horizontal sectional view of a part of an example of the extraction electrode plate.

Fig.7 is a horizontal sectional view of a part of another example of the extraction electrode plate.

Fig.8 is a horizontal sectional view of a part of third example of the extraction electrode plate.

Fig.9 is a vertical, sectional view of the electrode of third embodiment of this invention.

Fig.10 is a plan view of the extraction electrode of Fig.9.

An ion source introduces material gas into a chamber (11), excites the gas into plasma by electric discharge and pulls ion beams from the plasma by the action of electrode plates.

The electric discharge is either an arc discharge (DC), a glow discharge (DC or AC) or a microwave discharge. In many cases, many permanent magnets are mounted on an outer surface of the chamber in order to form cusp magnetic fields in the chamber.

[EMBODIMENT 1]

Fig.1 shows, as an example, a bucket type ion source having a chamber (6) and a filament (7) for inducing an arc discharge between the chamber (anode)(6) and the filament (cathode)(7) and for exciting material gas into plasma by the arc discharge. Since this invention relates only to an improvement of electrode plates, it is able to be applied to the type of ion sources.

The ion source chamber (6) has a gas inlet (8) for introducing material gas and an outlet for exhausting ion beams. Four electrode plates are mounted at the outlet of the chamber (6). The first is a plasma electrode plate (1). The second is an extraction electrode plate (2). The third is an acceleration electrode plate (4). The fourth is a grounded electrode plate (5). These electrode plates (1), (2), (4) and (5) have many ion holes (11), (12), (14) and (15) perforated along the same axial lines. Ion beams can pass through a series of the ion holes (11), (12), (14) and (15). A three-dimensional coordinate is defined here to take xy-planes in parallel with the electrode plates (1), (2), (4) and (5). The ion holes (11), (12), (14) and (15) are aligned in parallel with z-axis. Therefore, only the ion beams which enter the first ion hole (11) and make straight way along the z-direction can pass through all four ion holes (11), (12), (14) and (15).

The plasma electrode plate (1) is biased at the highest voltage. The extraction electrode plate (2) is biased at the second highest voltage. The acceleration electrode plate (4) is biased at a negative voltage. The grounded electrode plate (5) is grounded. A set of the plasma electrode plate (1), the acceleration plate (4) and the grounded electrode plate (5) is the most conventional assembly of electrode plates for ion sources.

However, the extraction electrode plate (2) is novel. Each ion hole (12) of the extraction electrode plate has a Wien filter for mass-separation of ions. This is the most important feature of this invention.

There are many permanent magnets (9) and (10) on the external surface of the chamber(6). The magnets (9) and (10) form cusp magnetic fields in the chamber (6). The cusp magnetic fields prevent plasma (18) from coming into contact with the inner surface of the chamber (6).

The filament (7) is heated by a filament power source (16). Material gas is introduced into the

chamber (6) through the gas inlet (8). An arc power source (17) applies positive voltage to the chamber (6) with regard to the filament (7). Thus, a DC voltage is established between the cathode filament (7) and the anode chamber (6). The heated filament (7) emits thermal electrons. The thermal electrons are accelerated by the DC voltage between the filament (7) and the chamber (6). Accelerated electrons collide with neutral gas molecules and excite them into plasma (18). Then an arc discharge is established between the cathode filament (7) and the chamber (6). The material gas is excited into plasma by the DC arc discharge.

A power source (23) biases the plasma electrode plate (1) at positive voltage. A power source (30) biases the chamber (6) further positively to the plasma electrode plate (1). A power source (24) applies a negative voltage to the acceleration electrode plate (4). A power source (19) biases the extraction electrode plate (2) negatively to the plasma electrode plate.

Since the feature of this invention is the extraction electrode plate (2) with ion holes (12) having individual Wien filters for mass separation, the ion holes (12) and the Wien filters will be explained by Fig.2 and Fig.3.

A Wien filter comprises a pair of permanent magnets (40) and (41) which face each other with different magnetic poles and a pair of parallel electrodes (42) and (43). The permanent magnets (40) and (41) form a static magnetic field in parallel with y-axis. The parallel electrodes (42) and (43) produce a static electric field in parallel with x-axis.

Four corners of the ion holes have corner pieces (35) which are made from non-magnetic material. In the embodiment, the permanent magnets are rectangular magnets. The direction of magnetism is perpendicular to the vertical line of the extraction electrode plate (2). The direction of magnetism is now denoted by y-direction. The magnets (40) and (41) generate magnetic field in y-direction. The parallel electrodes (42) and (43) produce an electric field in x-direction. Ion beams pass in z-direction through the ion holes (12).

A three dimensional coordinate is now defined by taking a central point of the front side of an ion hole (12) of the extraction electrode plate (2) as the original point in order to consider what movement an ion which has passed through the hole (12) will do. A center line l-m is z-axis. The central point of the rear side of the ion hole (12) is denoted by K. The length of the hole (12), i.e. the thickness of the extraction electrode plate (2), is designated by L_m. The central point of the front side of the acceleration electrode plate (4) is denoted by L. D is the diameter of the ion hole (14) of the acceleration electrode plate (4). L_d is the distance between the rear side of the extraction electrode plate (2) and the front side of the acceleration electrode plate (4).

Since a DC voltage is applied between the parallel electrodes (42) and (43), a static electric field E is established in x-direction. Permanent magnets (40) and (41) generate a static magnetic flux B in y-direction.

Velocity components of an ion are expressed by a vector (u, v, w). The static electric field is written as (E, 0, 0). The static magnetic flux is given by (0, B, 0). In the ion hole (7), an ion shall follow the equation of motion ;

$$M\,(du/dt) = qE - qwB \qquad (3)$$

$$M\,(dv/dt) = 0 \qquad (4)$$

$$M\,(dw/dt) = quB \qquad (5)$$

A complex variable ζ is defined by $\zeta = u + iw$. Eq.(3) and Eq.(5) can integrally be expressed by,

$$M\,(d\zeta/dt) = qE + iqB\zeta \qquad (6)$$

where M is the mass of the ion and q is the electric charge of the ion. Solution of Eq.(6) is given by,

$$\zeta = (iE/B) + C\exp(i\omega t) \qquad (7)$$

$$\omega = (qB/M) \qquad (8)$$

If initial conditions are imposed by $u = u_0$ and $w = w_0$ at $t = 0$, the velocity components u and w are,

$$u = u_0 \cos\omega t - \{w_0 - (E/B)\}\sin\omega t \qquad (9)$$

$$w = (E/B) + u_0 \sin\omega t + \{w_0 - (E/B)\}\cos\omega t \qquad (10)$$

" x_0 " denotes x at $t = 0$. The displacement x is obtained as,

$$x = x_0 + (u_0/\omega)\sin\omega t - \{w_0 - (E/B)\}(1 - \cos\omega t)/\omega \qquad (11)$$

Eq.(9) teaches us that an ion will follow a linear path without being bent in the ion hole (12) under the condition.

$$w_0 = (E/B) \qquad (12)$$

This is identical to Eq.(1). Eq.(2) makes the straight-pass condition relevant to the ion energy qEd and the ion mass M.

Substituting $t = L_m/w_0$, we obtain the velocity u and the displacement x at the outlet ($x = L_m$) of the Wien filter. A dimensionless parameter β is

defined by,

$$\beta = \omega L_m / w_0 \qquad (13)$$

u and x are written in brief as,

$$u = u_0 \cos\beta - \{ w_0 - (E/B) \} \sin\beta \qquad (14)$$

$$x = x_0 + (u_0/\omega) \sin\beta - \{ w_0 - (E/B) \}(1 - \cos\beta)/\omega \qquad (15)$$

If we wished to obtain rigorous, statistical efficiency of the Wien filter, we should investigate whether an ion having $x = x_0$ and $u = u_0$ at $t = 0$ could pass through the next ion hole of the acceleration electrode plate or not, taking the distributions of x_0 and u_0 into account. However, such estimation would be too difficult. For simplicity only the mass dispersion of ion beams having $x_0 = 0$ and $u = 0$ at $t = 0$ were considered. Since ion energy is still low at the extraction electrode plate (2), such assumption can not be so unrealistic.

In brief, approximation of $\sin\beta = \beta$ is now employed, because β is much less than 1 ($0 < \beta \ll 1$). The displacement of the ion at the front surface of the acceleration electrode plate (3) is now denoted by X.

$$X = -\{ w_0 - (E/B) \}(1 - \cos\beta)/\omega - \{ w_0 - (E/B) \} + L_d \sin\beta / w_0 \qquad (16)$$

$$\fallingdotseq -\{ w_0 - (E/B) \} \{ (L_d + L_m/2)\, \omega L_m \} / w_0^2 \qquad (17)$$

Since ion energy is the same despite the difference of mass, because the energy of acceleration before the extraction electrode plate is the same. Thus, z-component w_0 of the initial velocity is solely determined by the mass M. Then, such an ion which satisfies the condition $w_0 = E/B$ is designated by M_0. M_0 is the mass of the ions whose beams are required to treat objects. Other ions whose mass is not M_0 should be eliminated before reaching objects. In order to estimate the performance of mass separation, the deviation of an ion whose mass deviates by δM from M_0 ($M = M_0 + \delta M$) at the front surface of the acceleration electrode plate (4) will be now calculated. For such ions, the equation $w_0 = E/B$ does not hold. w_0 deviates from E/B (constant value) by some amount in proportion to mass difference δM.

$$w_0 - (E/B) = \{ 2qV_0/(M_0 + \delta M) \}^{1/2} - (2qV_0/M_0)^{1/2} \qquad (18)$$

$$\fallingdotseq -(2qV_0)^{1/2} \delta M / (2M_0^{3/2}) \qquad (19)$$

Substituting Eq.(19) into Eq.(17), we obtain the displacement X of the ion.

$$X = (\delta M \omega L_m)(L_d + L_m/2)/(2M_0 w_0) \qquad (20)$$

Here, the definition of the variables is now recited in order to deter the significance of equations from being ambiguous. δM is the difference of mass, ω is an angular cyclotron frequency of the ion, L_m is the length of the ion hole (12) and L_d is the distance from the rear surface of the extraction electrode plate to the front surface of the acceleration electrode plate. M_0 is the standard, reference mass. w_0 is an initial velocity of the ion. Eq.(20) teaches that such ions with the mass bigger than M_0 ($\delta M > 0$) will deviate from the axial line to the plus x-direction ($x > 0$) at the acceleration electrode plate (4) and other ions with the mass lighter than M_0 ($\delta M < 0$) will deviate from the axial line to the minus x-direction ($x < 0$). The displacement is in proportion to the substantial length ($L_d + L_m/2$) of free flight of ion, in proportion to the length L_m of the Wien filter but in reverse proportion to the mass M_0 or the velocity w_0.

The diameter of the next ion hole (14) of the acceleration electrode plate (4) is denoted by Δ_x($= D$). An ion which has flown along the central line OK through the Wien filter can pass through the hole (14) of the acceleration electrode plate (4), if $|x| < \Delta_x/2$. Since some portions of ion beams flow near the side wall of the filter holes (12), $|x| < \Delta_x$ is the general condition for passing through the ion holes (14) of the acceleration plate (4). Then substitution of x with Δ_x gives us the formula of resolution power of the Wien filter.

$$(M_0/\delta M) = (\omega L_m)(L_d + L_m/2)/(2\Delta_x w_0) \qquad (21)$$

Resolution power, electric field or magnetic field will be considered by referring to two examples.

[EXAMPLE 1]

Energy at the extraction electrode plate ... $qV_0 = 1$ keV
Diameter of ion holes of the extraction electrode plate .. $\Delta_x = 2$ mm
Length of ion holes of the extraction electrode plate .. $L_m = 20$ mm
Distance between the extraction electrode and the acceleration electrode ... $L_d = 20$ mm

The reference mass M_0 is 31. The desired ion is a single-charged phosphorus ion P^+. The initial velocity w_0 is calculated as,

$$w_0 = 7.86 \times 10^4 \text{ m/sec}$$

These parameters determine the resolution power as a function of magnetic flux

$M_0 / \delta M = 5.9 \times B$ (22)

The relation between E and B is

$E = 7.86 \times 10^4 B$ (23)

(i) ^{31}P and ^{52}Cr : ^{52}Cr is mixed in the ion beams of ^{31}P. In order to separate ^{52}Cr ions from ^{31}P ions, the resolution power shall be at least

$M_0/\delta M = 31 / (52 - 31) = 1.48$ (24)

Eq.(22), Eq.(23) and Eq.(24) determine the magnetic flux B and the electric field E for the resolution power.

$B = 0.25$ (Tesla) (25)

$E = 1.97 \times 10^4$ V/m (26)

(ii) ^{31}P and $^{28}N_2$: $^{28}N_2$ is mixed in the ion beams of ^{31}P. $^{28}N_2$ is more difficult to separate by mass than ^{52}Cr because of smaller difference of mass. The resolution power shall be at least,

$M_0/\delta M = 31 / (31 - 28) = 10.3$ (27)

Therefore, Eq.(22), Eq.(23) and Eq.(27) produce

$B = 1.7$ (Tesla) (28)

$E = 1.37 \times 10^5$ V/m (29)

[EXAMPLE 2]

Energy at the extraction electrode plate ... qV_0 = 100 eV
Diameter of ion holes of the extraction electrode plate .. Δ_x = 2 mm
Length of ion holes of the extraction electrode plate .. L_m = 20 mm
Distance between the extraction electrode and the acceleration electrode ... L_d = 20 mm

The reference mass M_0 is 31. The desired ion is also a single-charged phosphorus ion P^+.

$M_0 / \delta M = 18.7 \times B$ (30)

The relation between E and B is

$E = 2.49 \times 10^4 B$ (31)

(i) ^{31}P and ^{52}Cr : Separation of ^{31}P from ^{52}Cr requires resolution power Ma/δM of at least 1.48. Therefore, the magnetic flux B and the electric field E are calculated as

$B = 0.079$ (Tesla) (32)

$E = 1.97 \times 10^3$ V/m (33)

(ii) ^{31}P and $^{28}N_2$: Separation of ^{31}P from $^{28}N_2$ corresponds to the resolution power of 10.3.

$B = 0.551$ (Tesla) (34)

$E = 13.7 \times 10^7$ V/m (35)

These examples show the strengths of the electric field and the magnetic flux are little. This is mainly because the ion energy is low enough at the Wien filters. This invention separates ions by mass before being accelerated enough. The energy of ions at the extraction electrode plate is less than 1 keV. In usual cases, the energy is as low as 100 eV. Mass separation of ion beams with low energy requires a low magnetic flux and a low electric field.

[EMBODIMENT 2]

EMBODIMENT 1 has drawbacks. The extraction electrode plate (2) is biased with a high positive voltage. The next acceleration electrode plate (4) is biased with a negative voltage. The voltage drop between the extraction electrode plate (2) and the acceleration electrode plate (4) is considerably large. Thus, the ions which have been accelerated therebetween and have collided with the acceleration electrode plate (2) have large kinetic energy. For example, the bias of the electrodes plates is assumed to be

plasma electrode plate ... 10 kV
extraction electrode plate ... 9.6 kV
acceleration electrode plate ... - 0.5 kV
grounded electrode plate ... 0 kV

In this case, the ions whose mass is less than M_0 (underweight) or more than M_0 (overweight) will collide with the acceleration electrode plate with the high kinetic energy of 10.5 keV. The bombardments of overweight or underweight ions generate a lot of secondary electrons from the acceleration electrode plate. The secondary electrons induce a parasitic discharge between the acceleration electrode plate and the extraction electrode plate. The discharge will perturb the bi-

ases of the electrode plates, dissipate electric power and excite unnecessary ions between the electrode plates. This is a drawback. Therefore, such an occurrence of parasitic discharge shall be avoided.

Another defect is low resolution power. Since ions are accelerated to z-direction by the electric field between the extraction electrode plate (2) and the acceleration electrode plate (4). Even off-axis ions which have flown along skew directions will pass through the ion holes (14) of the acceleration electrode plate (4) by the attraction force of the acceleration electrode plate. Namely, even overweight ions or underweight ions will be able to pass through the ion holes (14). The focussing function of the strong electric field produced between the extraction electrode plate and the acceleration electrode plate deteriorates resolution power. An embodiment with high resolution power being immune from the occurrence of secondary electrons will now be proposed.

Embodiment 2 has five electrode plates, i.e. a plasma electrode plate (1), an extraction electrode plate (2), a mass-separation electrode plate (3), an acceleration electrode plate (4) and a grounded electrode plate (5). Fig.4 shows the schematic view of embodiment 2. Fig.5 shows the sectional view of the electrode plates. Fig.6 shows a plan view of the extraction electrode plate. Embodiment 2 has five electrode plates instead of four electrode plates. The mass-separation electrode plate (3) is newly introduced in embodiment 2.

Five electrode plates (1) to (5) are in parallel installed at the outlet of the ion source chamber (6). They have a lot of ion holes perforated perpendicularly to the surface. The ion holes of all electrode plates (1) to (5) are aligned along with parallel axial lines. The newly-introduced mass-separation electrode plate (3) has smaller ion holes than the extraction electrode plate (2). Unlike the acceleration electrode plate (4), the mass-separation electrode plate (3) is applied with positive high voltage slightly lower than the bias of the extraction electrode plate (2). Thus, ions are not accelerated so fast between the extraction electrode plate (2) and the mass-separation electrode plate (3).

Like embodiment 1, the chamber (6) has an filament (7) which is heated by a filament power source (16). The chamber (6) can be made vacuum by a vacuum pump. Material gas is introduced through a gas inlet (8). Permanent magnets (9) and (10) are installed on the outer wall of the chamber (6) in order to form cusp magnetic field in the chamber.

The chamber (6) is positively biased by an arc power source (17) with regard to the filament (7). The arc power source (17) induces arc discharge between the chamber (anode)(6) and the filament (cathode)(7). The DC arc discharge excites the material gas into plasma. Five electrode plates (1) to (5) are mounted at the outlet of the chamber (6). The plasma electrode plate (1) is positively biased by a power source (23). However, the voltage of the plasma electrode plate (1) is slightly lower than that of the chamber (6).

The extraction electrode plate (2) is biased by a power source (19) slightly lower than the plasma electrode plate (1). The extraction electrode plate (2) has a lot of Wien filters at the ion holes. As a Wien filter requires two different voltage levels, two reversely biasing power sources (20) and (21) are provided in common to the Wien filters.

The mass-separation electrode plate (3) is biased slightly lower than the extraction electrode plates (2). The acceleration electrode plates (4) is biased with negative voltage. The grounded electrode plate (5) is grounded (V = 0).

For example, the biases of the electrode plates are settled as ;

plasma electrode plate ... 10 kV
extraction electrode plate ... 9.9 ~ 9.6 kV
mass-separation electrode plate ... 9.7 ~ 8.0 kV
acceleration electrode plate ... -0.5 ~ -1 kV
grounded electrode plate ... 0 V

Namely, ions have low energy and low speed till they have passed through the ion holes of the mass-separation electrode plate (3). Ions are mainly accelerated between the mass-separation electrode plate (3) and the acceleration electrode plate (4).

Each ion hole of every electrode plate is aligned along a central line m - n. The ion holes (12) of the extraction electrode plate (2) are provided with Wien filters. A Wien filter consists of four permanent magnets (28) and a pair of common electrodes (27a) and (27b). In Fig.6, the ion holes aligned in y-direction have common electrodes (27a) and (27b). (27b) is positively biased by the power source (21). (27a) is negatively biased by the power source (20). Thus, static electric field E is generated in x-direction. Two electrodes (27a) and (27b) belonging to the same Wien filters are separated in the middle by insulators (29). Neighboring electrodes (27a) and (27b) belonging to different Wien filters are separated in the middle by another insulator (30). The insulators (29) and (30) effectively prevent electric field from inducing discharge between the electrodes (27a) and (27b).

Four permanent magnets (28) are aligned in the same direction. They form magnetic field in the ion holes in y-direction. The electric field (x-direction) and the magnetic field (y-direction) of the Wien filter give opposite forces to the ions flying in z-direction. Such an ion with reference mass M_0 having a certain velocity w_0 = E/B can pass straightly through the Wien filter, because the

opposite forces are exactly balanced. Overweight ions with lower speed bend to the direction of the electric field. Underweight ions with higher speed bend to the direction reverse to the electric field. Such bent ion beams (26) collide with the mass-separation electrode plate (3) and lose their energy. Thus, underweight ions and overweight ions are eliminated from the ion beams. The ion holes (13) of the mass-separation electrode plate (3) is smaller than that of the extraction electrode plate (2). Thus, the smaller ion holes (13) are seen behind the bigger ion holes (12) in Fig.6. The smaller ion holes improve the resolution power of the Wien filters. This is one advantage of embodiment 2.

The other advantage is no occurrence of secondary electrons at the mass-separation electrode plate, because ions have insufficient energy at the mass-separation electrode plate (3) because of the small difference of voltage between the extraction electrode plate (2) and the mass-separation electrode plate (3). Thus, no parasitic discharge occurs between the extraction electrode plate and the mass-separation electrode plate.

[EMBODIMENT 3]

Fig.7 exhibits embodiment 3. Ion holes are disposed at corners of a regular triangle. Electrodes (27) of neighboring Wien filters are unified unlike embodiments 1 and 2. The left electrode is positively biased. The middle electrode (27c) is negatively biased. The right electrode (27d) is positively biased. Therefore, the direction of the electric field changes in x-direction periodically. Therefore, the magnetic field must also change in x-direction. In the first column, the magnetic field is directed to minus y-direction. In the second column, it is directed to plus y-direction. Both the electric field and the magnetic field change in x-direction. Embodiment 3 simplifies the structure of electrodes (27) by reducing the number of electrode to half. In the example, gaps (31) of electrodes are not filled with insulators.

[EMBODIMENT 4]

Fig.8 shows another embodiment. The ion holes are arranged periodically like lattice work. The electrodes (27g) are unified with regard to neighboring columns of Wien filters. Thus, the periodicity of the electrodes is twice as long as embodiment 2. The number of permanent magnets is also reduced to half. Two parallel magnets belong to neighboring Wien filters in the same column. The directions of permanent magnets are the same in the Wien filters in the same column. However, the direction of permanent magnet changes in x-direction. Embodiment 4 can also simplify the structure of electrodes. The directions of the magnetic field and the electric field change in x-direction.

Directions of bending of underweight ions or overweight ions are different in the Wien filters aligned in x-direction.

[EMBODIMENT 5]

Fig.9 and Fig.10 show another embodiment. Like embodiments 3 or 4, the electrodes of neighboring columns of Wien filters are unified. Thus, the directions of magnetic field of the Wien filters of the same column are the same. However, the directions of the magnetic field change in the neighboring columns, The ion holes of the extraction electrode plate are not circular but square in the embodiment. One set of electrodes is biased at minus 200 V, and the other set of electrodes is biased at plus 200 V. The disposition of the electrodes and the permanent magnets are similar to embodiment 3 shown in Fig.7. However, embodiment 5 has six electrode plates. The electrode plates are a plasma electrode plate (1), a pulling-out electrode plate (51), a filter electrode plate (52), a mass-separation electrode plate (3), an acceleration electrode plate (4) and a grounded electrode plate (5). Namely, the extraction electrode plates (2) of embodiment 1 to 5 have been divided into the pulling-out electrode plate (51) and the filter electrode plate (52). Although the pulling-out electrode plate plays the same role as the extraction electrode plate regarding the electrostatic action to ions, one of the divided electrode plate is called as pulling-out electrode plate in order to avoid confusion. The square ion holes of the filter electrode plates improve the distribution of electric field in the holes. Circular ion holes would disturb the electric field near the electrodes. In order to make uniform, parallel electric field, the square ion holes are more appropriate than circular ion holes. The other electrode plates, i.e. the plasma electrode plate (1), the pulling-out electrode plate (51), the mass-separation electrode plate (3), the acceleration electrode plate (4) and the grounded electrode plate (5) have circular ion holes in the example. However, the circular ion holes can be replaced by square ion holes.

In the example, the voltages of the electrode plates are ;

plasma electrode plate ... 10 kV
pulling-out electrode plate ... 9 kV
filter electrode plate ... 9 kV
mass-separation electrode plate ... 9 kV
acceleration electrode plate ... -0.2 kV
grounded electrode plate ... 0 V

The biases of the electrodes of the filter elec-

trode plate are +200 V and -200 V. The difference of voltage of the filter electrodes is 400 V. Namely, the voltage of the plus electrodes is 9.2 kV. The voltage of the minus electrodes is 8.8 kV. In the example, three electrode plates, i.e. pulling out, filter and mass-separation have the same voltage. However, slight voltage decrease is also allowable between the pulling-out electrode plate and the filter electrode plate or between the filter electrode plate and the mass-separation electrode plate.

Embodiments 1 to 5 have an unified extraction electrode plate (2). In such a disposal of electrodes, the horizontal electric field induced by the filter electrodes (27a) and (27b) is likely to disturb the vertical, pulling electric field between the plasma electrode plate (2) and the extraction electrode plate (3) made by the power source (19). The perturbation of the vertical electric field would induce horizontal (x-direction) aberration of ion beams in front of the extraction electrode plate. Since this embodiment has divided the extraction electrode plate into the pulling out electrode plate and the filter electrode plate, no perturbation of vertical electric field occurs as far as the pulling-out electrode plate. Ion beams can be pulled out straightly by the pulling-out electrode plate (51).

This invention has advantages as follows,

(1) So far large area type ion source has no mass-separation device. The inventors have provided large area type ion source with a mass-separation device for the first time.

(2) Since the ion beams pass through multi-type Wien filters before being accelerated, the Wien filters require no high electric field nor high magnetic field. Low electric filed and low magnetic field make the cost of manufacturing Wien filters cheaper.

(3) Instead of a single big magnet which bends ion beams in an arc curve, many small Wien filters are used (multi-type Wien filter). Thus, the small size of individual Wien filter enables us further to reduce the electric field and the magnetic field.

(4) Embodiment 2 has furthermore two advantages, i.e. high resolution power and suppression of parasitic discharge.

(5) Embodiment 5 can pull ion beams in a straight direction perpendicular to the plate by the pulling-out electrode plate, because the extraction electrode plate is divided into the pulling-out electrode plate and the filter electrode plate.

Claims

1. An ion source having a mass-separation device which converts material gas into plasma and exhausts ion beams from the plasma comprising a vacuum chamber having a gas inlet and an ion outlet, a vacuum pump for evacuating the chamber, a discharge device for generating a discharge in the chamber to excite material gas into plasma, a plasma electrode plate having ion holes and being installed at the outlet of the chamber, the plasma electrode plate, in use, being biased at a high positive voltage !!!!!! lower than the voltage of the chamber, an extraction electrode plate having ion holes at corresponding positions and being installed next to the plasma electrode plate, the extraction electrode, in use, being biased at a high positive voltage lower than the voltage of the plasma electrode plate, an acceleration electrode plate having ion holes at corresponding positions and being installed next to the extraction electrode at the outlet of the chamber, the acceleration electrode plate, in use, being biased at a small negative voltage, a grounded electrode plate having ion holes at corresponding positions as the acceleration electrode plate and being installed next to the acceleration electrode plate at the outlet of the chamber, characterized in that each ion hole of the extraction electrode is provided with a Wien filter including permanent magnets which face each other and have different magnetic poles and are arranged to produce a magnetic field generally perpendicular to an axial direction of the ion holes, and electrodes facing each other and being biased at different voltages for producing an electric field generally perpendicular both to the magnetic field and to the axial direction, the arrangement being such that, in use, ion beams whose mass is equal to a reference mass M_0 follow a generally linear path through the Wien filters of the extraction electrode plate by receiving substantially the same but reverse forces from the electric field and the magnetic field, but other ion beams whose mass is not equal to the reference mass M_0 follow a curved or non-linear path through the Wien filters by receiving different, reverse forces from the electric field and the magnetic field, and collide with the next acceleration electrode plate.

2. An ion source as claimed in claim (1), wherein each Wien filter of the ion holes of the extraction electrode plate comprises a pair of permanent magnets aligned on opposite sides of the ion hole with the same direction of the magnetism and a pair of common electrodes aligned on another opposite sides of the holes.

3. An ion source as claimed in claim (1), wherein the difference of voltage between the plasma

electrode plate and the extraction electrode plate is less than 1 kV and the kinetic energy of an ion at the Wien filter of the extraction electrode plate is less than 1 keV.

4. An ion source as claimed in claim (3), wherein the discharge device comprises filament which when heated emits thermal electrons, a DC power source applying positive voltage to the chamber with regard to the filament, and an arc discharge is induced between the chamber and the filament.

5. An ion source as claimed in claim (3), wherein the chamber has permanent magnets on the outer surface in order to form cusp magnetic field operable to confine the plasma in the chamber.

6. An ion source as claimed in claim (3), wherein the discharge device comprises a microwave oscillator, and a wave guide for guiding microwave from the microwave oscillator into the chamber, the microwave energy introduced into the chamber exciting the material gas into plasma.

7. An ion source as claimed in claim (3), wherein the discharge device comprises a microwave oscillator, a wave guide for guiding microwave from the microwave oscillator into the chamber and a coil installed around the outer wall of the chamber for making an axial magnetic field, the axial magnetic field being arranged to rotate electrons with the same frequency as the microwave, and the microwave energy exciting the material gas into plasma.

8. An ion source having a mass-separation device which converts material gas into plasma and exhausts ion beams from the plasma comprising a vacuum chamber having a gas inlet and an ion outlet, a vacuum pump for evacuating the chamber, a discharge device for generating discharge in the chamber to excite material gas into plasma, a plasma electrode plate having ion holes and being installed at the outlet of the chamber, the plasma electrode plate, in use, being biased at a high positive voltage of the chamber, an extraction electrode plate having ion holes at corresponding position and being installed next to the plasma electrode plate at the outlet of the chamber, the extraction electrode, in use, being biased at a high positive voltage lower than the voltage of the plasma electrode plate, a mass-separation electrode plate having ion holes at corresponding positions and being installed next to the extraction electrode plate, the mass-separation electrode, in use, being biased at a high positive voltage lower than the voltage of the extraction electrode plate, an acceleration electrode plate having ion holes at corresponding positions to the mass-separation electrode, and being installed next to the mass-separation electrode, and being installed next to the mass-separation electrode at the outlet of the chamber, the acceleration electrode plate being biased at a small negative voltage and a grounded electrode plate having ion holes at corresponding positions as the acceleration electrode plate and being installed next to the acceleration electrode plate at the outlet of the chamber, characterized in that each ion hole of the extraction electrode plate is provided with a Wien filter including permanent magnets which face each other and have different magnetic poles and are arranged to produce a magnetic field generally perpendicular to an axial direction of the ion holes, and electrodes facing each other and being biased at different voltages for producing an electric field generally perpendicular both to the magnetic field and to the axial direction, the arrangement being such that, in use, ion beams whose mass is equal to a reference mass M_0 follow a generally linear path through the Wien filters of the extraction electrode plate by receiving substantially the same but reverse forces from the electric field and the magnetic field, but the other ion beams whose mass is not equal to the reference mass M_0 follow a curved or non-linear path through the Wien filters by receiving different, reverse forces from the electric field and the magnetic field, and collide with the next mass-separation electrode plate.

9. An ion source as claimed in claim (8), wherein each Wien filter of the ion holes of the extraction electrode plate comprises two pairs of permanent magnets aligned on opposite sides of the ion hole with the same direction of magnetism and a pair of common electrodes aligned on another opposite sides of the hole, the pair of electrodes being separated by an insulator, the electrodes belonging to the neighboring Wien filters in the direction of electric field being separated by another insulator and the directions of electric field and the magnetic field being the same with regard to all Wien filters.

10. An ion source as claimed in claim (8), wherein each Wien filter of the ion holes of the extraction electrode plate comprises half of two pairs of permanent magnets aligned on opposite

sides of the ion hole with the same direction of magnetism and belonging in common to the neighboring Wien filters and half of a pair of electrodes aligned on opposite sides of the ion holes and belonging in common to all the Wien filters along the line parallel to the magnetic field.

11. An ion source as claimed in claim (9) or (10), wherein the Wien filters are aligned lengthwise and crosswise in the extraction electrode.

12. An ion source as claimed in claim (9), wherein the difference of voltage between the extraction electrode plate and the mass-separation electrode plate is less than 2 kV.

13. An ion source as claimed in claim (12), wherein the difference of voltage between the plasma electrode plate and the extraction electrode plate is less than 1 kV.

14. An ion source as claimed in claim (8), wherein the ion holes of the mass-separation electrode plate are smaller than that of the extraction electrode plate.

15. An ion source having a mass-separation device which converts material gas into plasma and exhausts ion beams from the plasma comprising a vacuum chamber having a gas inlet and an ion outlet, a vacuum pump for evacuating the chamber, a discharge device for generating a discharge in the chamber to excite material gas into plasma, a plasma electrode plate having ion holes and being installed at the outlet of the chamber, the plasma electrode plate, in use, being biased at a high positive voltage lower than the voltage of the chamber, a pulling-out electrode plate having ion holes at positions corresponding to the plasma electrode plate and being installed next to the plasma electrode plate at the outlet of the chamber, a filter electrode plate having ion holes at positions corresponding to the pulling-out electrode plate and being installed next to the pulling-out electrode plate, the filter electrode plate, in use, being biased at a high positive voltage equal to or lower than the voltage of the pulling-out electrode plate, a mass-separation electrode plate having ion holes at positions corresponding to the filter electrode plate and being installed next to the filter electrode plate at the outlet of the chamber, the mass-separation electrode plate, in use, being biased at a high positive voltage equal or lower than the voltage of the filter electrode, an acceleration electrode having ion holes at positions corresponding to the mass-separation electrode plate and being installed next to the mass-separation electrode plate at the outlet of the chamber, the acceleration electrode plate, in use, being biased at a negative small voltage, and a grounded electrode plate having ion holes at positions corresponding to the acceleration electrode plate and being installed next to the acceleration electrode plate at the outlet of the chamber, characterized in that each ion hole of the filter electrode is provided with a Wien filter including permanent magnets which face each other and have different magnetic poles and are arranged to produce a magnetic field generally perpendicular to an axial direction of the ion holes, and electrodes facing each other and being biased at different voltages for producing an electric field generally perpendicular both to the magnetic field and to the axial direction, the arrangement being such that, in use, ion beams whose mass is equal to a reference mass M_0 follow a generally linear path through the Wien filters of the filter electrode plate by receiving substantially the same but reverse forces from the electric field and the magnetic field, but other ion beams whose mass is not equal to the reference mass M_0 follow a curved or non-linear path through the Wien filters by receiving different, reverse forces from the electric field and the magnetic field, and collide with the next mass-separation electrode plate.

16. An ion source as claimed in claim (15), wherein the filter electrode plate has square ion holes.

17. An ion source as claimed in claim (15), wherein the difference of voltages between the plasma electrode and the filter electrode plate is less than 2 kV.

18. An ion source as claimed in claim (17), wherein the difference of voltages between the filter electrode plate and the mass-separation electrode plate is less than 2kV.

FIG. 1

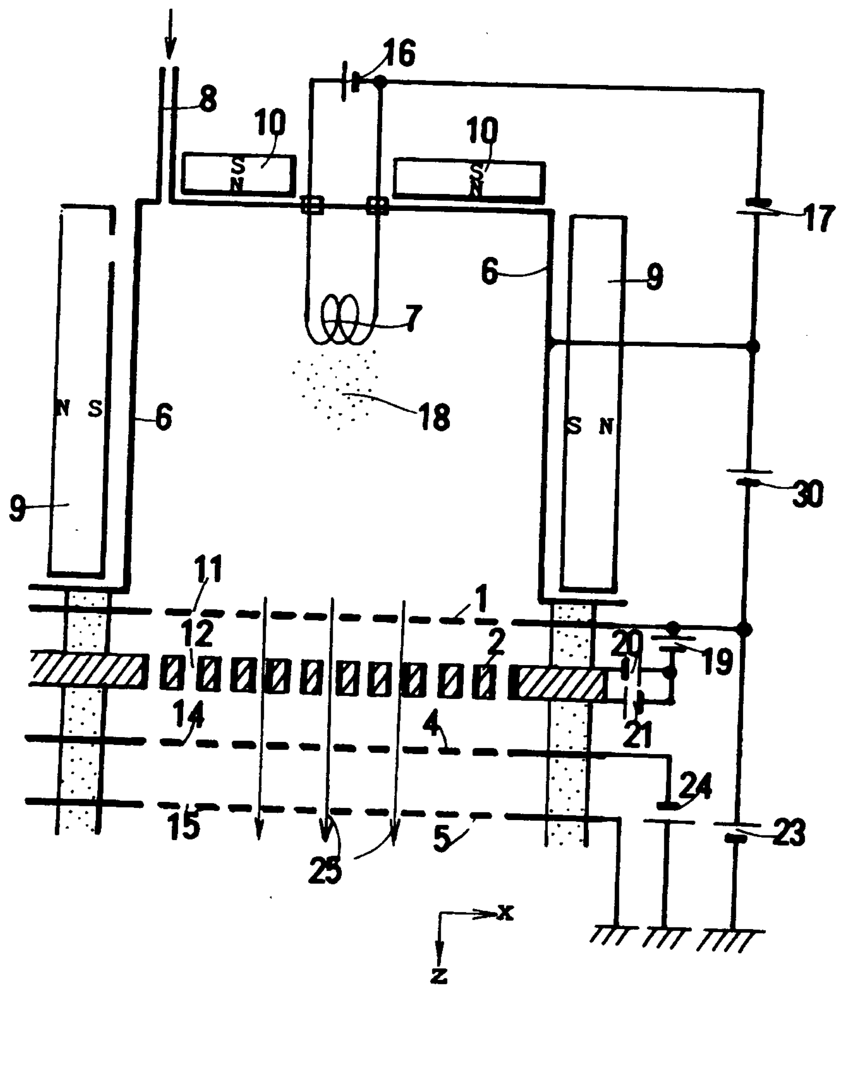

FIG. 2

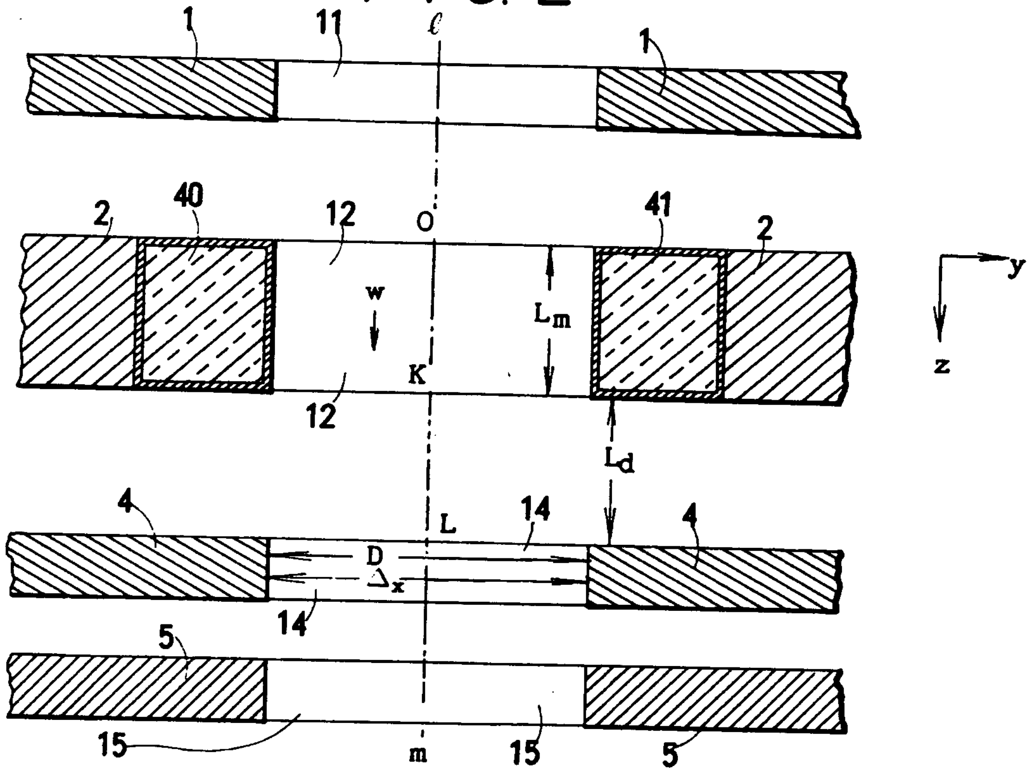
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FIG. 3

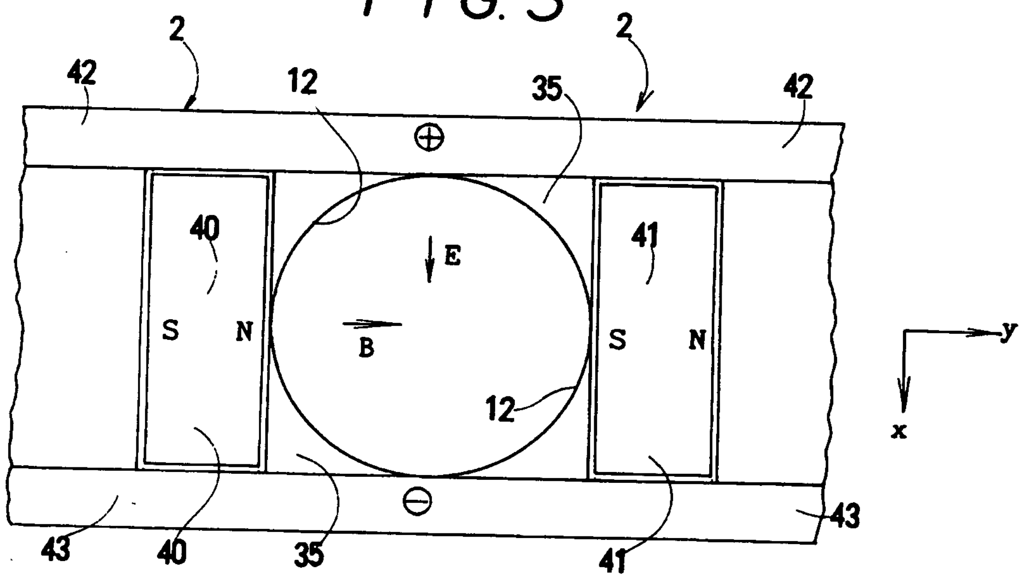
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FIG. 4

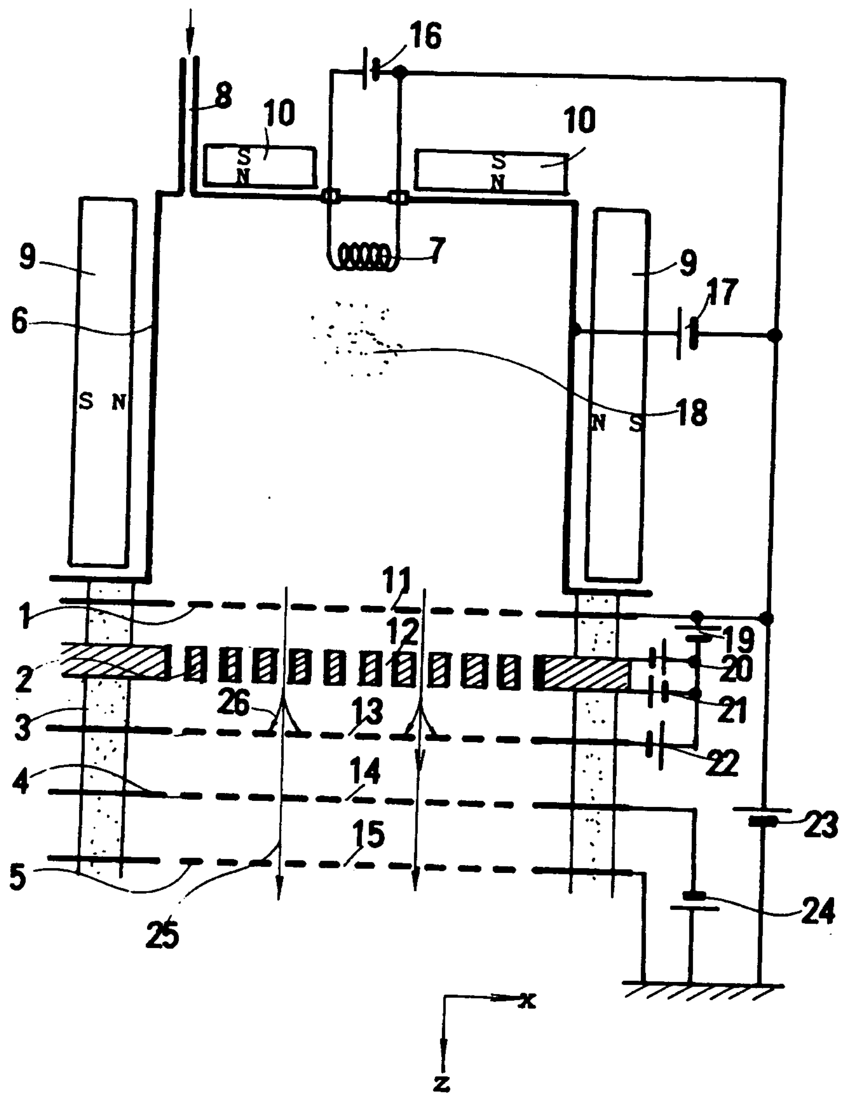
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FIG. 5

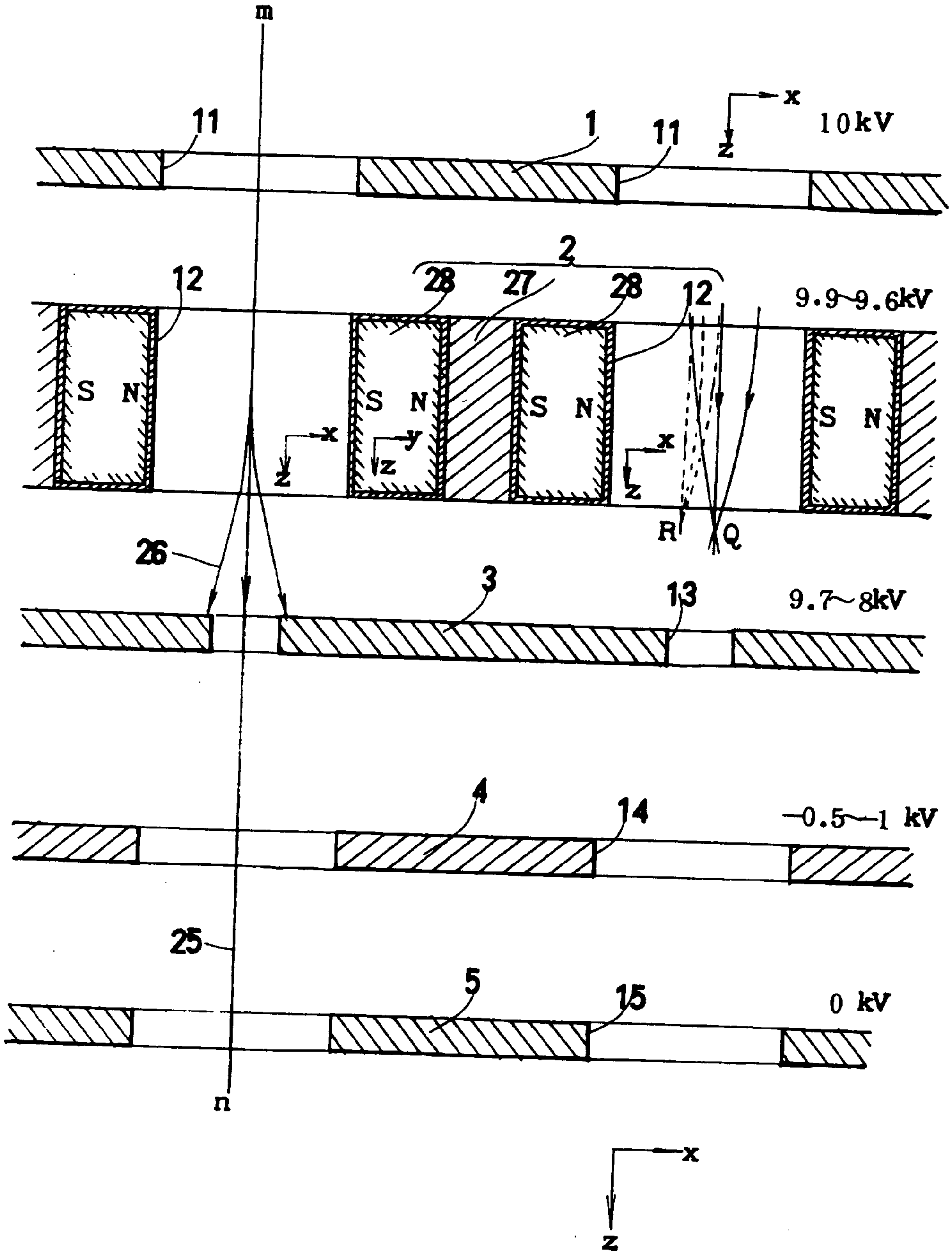
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FIG. 6

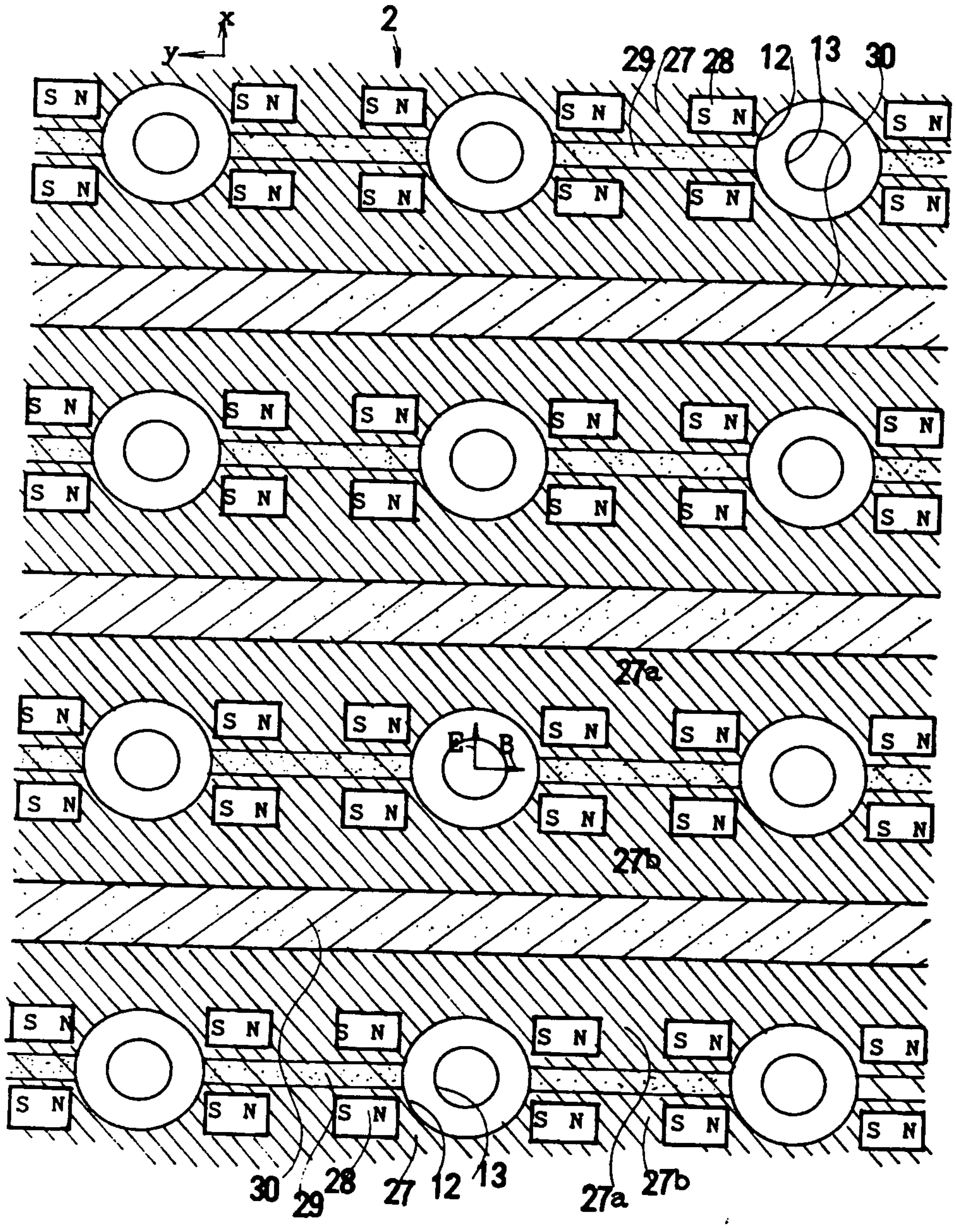

FIG. 7

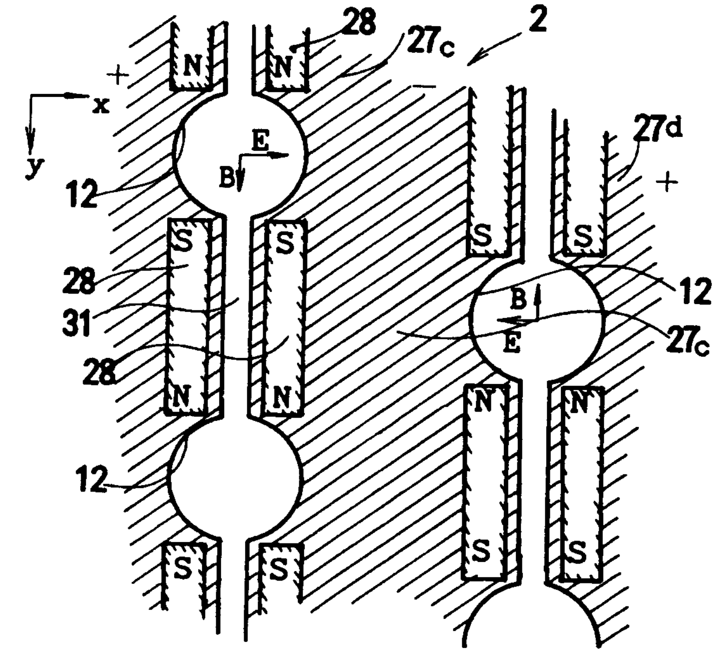
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FIG. 8

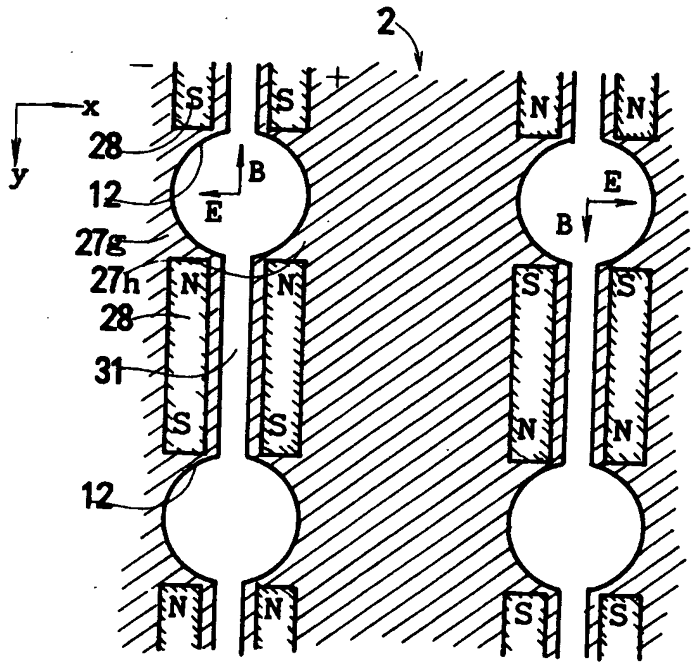
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FIG.9

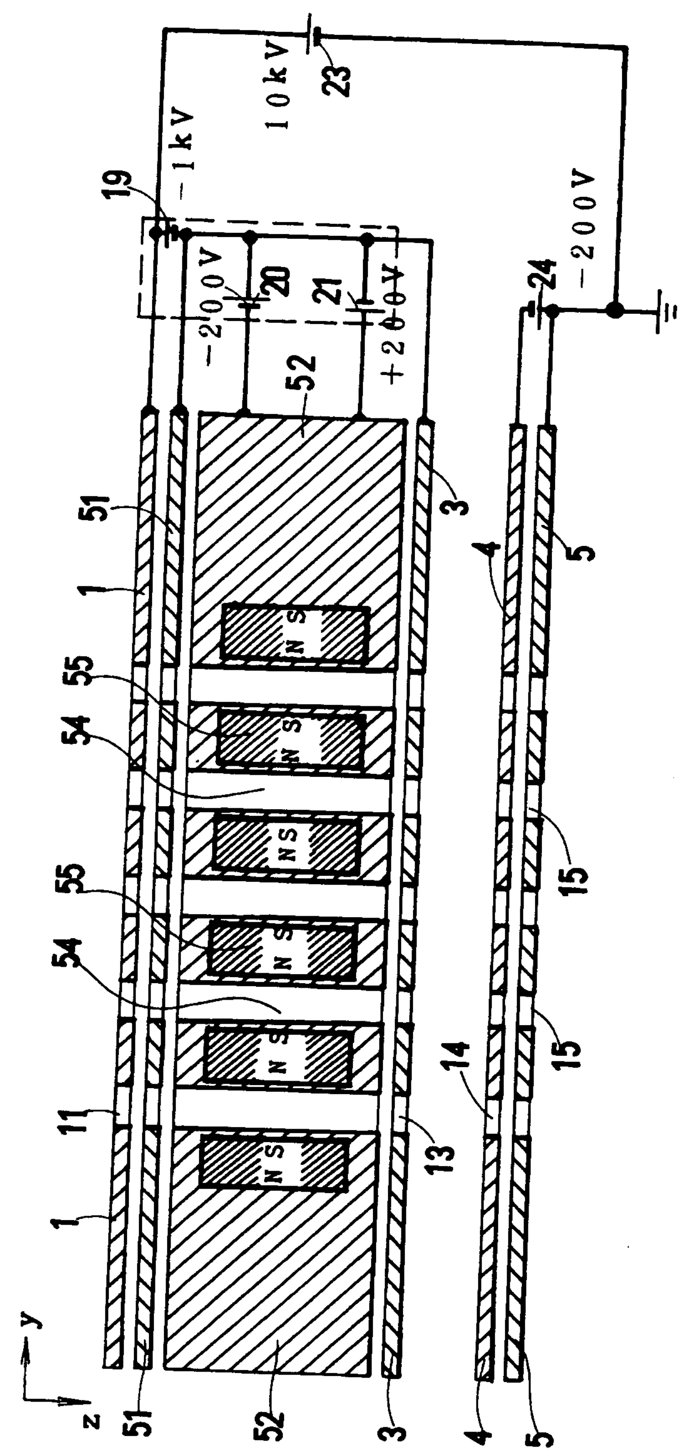

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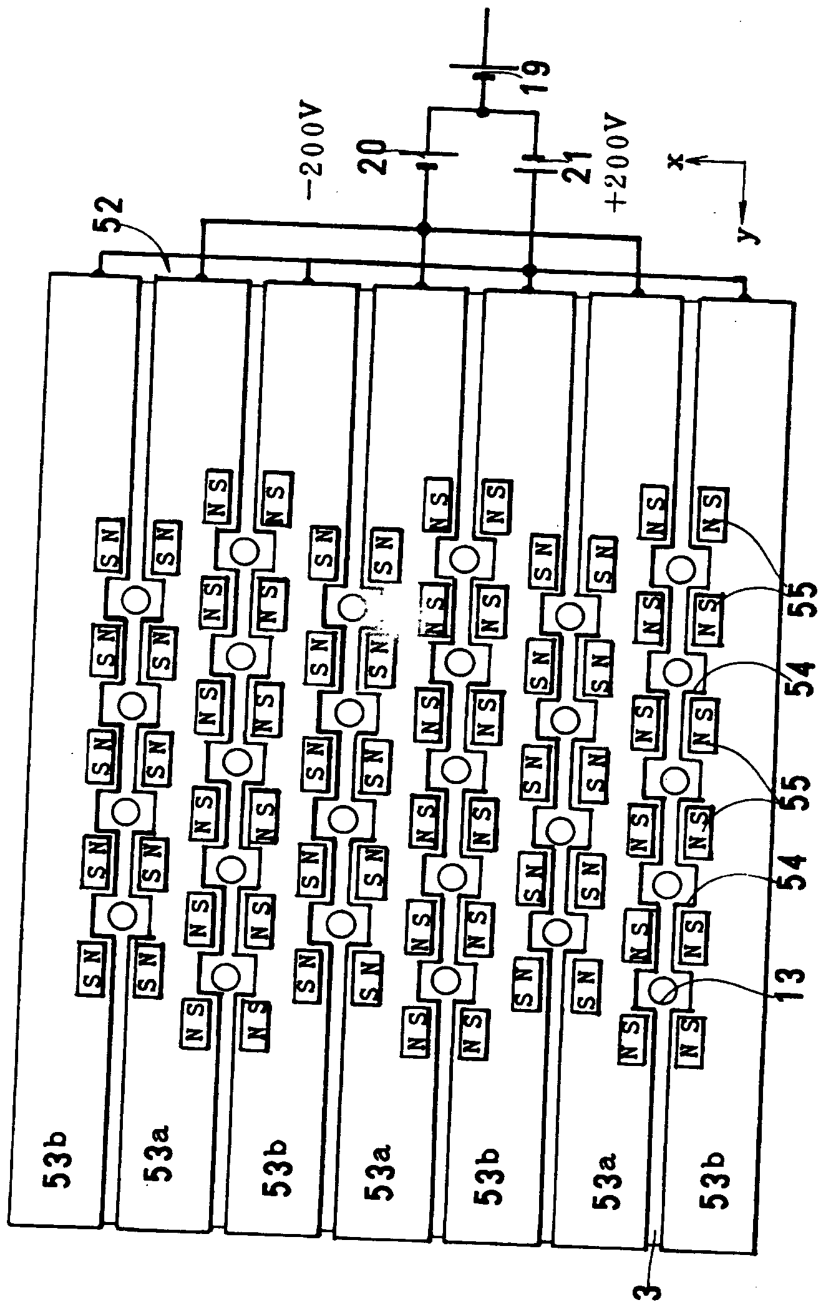
FIG. 10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European Patent Office

EUROPEAN SEARCH REPORT

Application Number

EP 92 30 1189

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int. Cl.5)
A	FR-A-2 610 138 (EVRARD ROBERT) * abstract; figure 1 *	1,8,15	H01J27/02 H01J37/08
A	PATENT ABSTRACTS OF JAPAN vol. 010, no. 332 (E-453)12 November 1986 & JP-A-61 138 437 (HITACHI) 25 June 1986 * abstract *	1,8,15	
			TECHNICAL FIELDS SEARCHED (Int. Cl.5)
			H01J

1

The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
THE HAGUE	07 OCTOBER 1992	HULNE S.L.

CATEGORY OF CITED DOCUMENTS

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D : document cited in the application
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(19) Europäisches Patentamt
European Patent Office
Office européen des brevets

(11) Publication number: 0 525 927 B1

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(51) Int. Cl.[6]: H01J 27/02, H01J 37/08

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(54) Ion source having a mass separation device.

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(56) References cited:
FR-A- 2 610 138
PATENT ABSTRACTS OF JAPAN, vol. 010, no. 332 (E-453) 12 November 1986 & JP-A-138 437

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EP 0 525 927 B1

Description

This invention relates to a large area type ion source having a mass separation device. An ion source is a device which converts a gas introduced into a vacuum chamber into plasma and makes ion beams by pulling ions out.

Ion sources have been used for various purposes in various fields of technology, e.g. for doping impurities into semiconductor devices, liquid crystal TFT or solar cells, for etching objects by ion beams, for cutting or polishing by ion sputtering, for depositing thin films by ion beams, for improving the quality of objects or for processing objects on some purpose.

Narrow ion beams with small diameter have also been utilized. In general, narrow ion beams have been used more frequently for measuring properties of objects than for processing or treating objects, because narrow ion beams are inconvenient to process or treat objects with high yield.

In the case of narrow ion beams, it is easy to mount a mass separation device at a point of a passage of ion beams. A mass separation device is a device which bends the paths of ion beams by magnets into curved paths with different curvatures, distinguishes ions by the difference of mass and permits the ions with predetermined mass to pass through the device. Such ion sources that produce narrow ion beams are called here zero-dimension type.

However, if the purpose of an ion source is to process objects, wide ion beams are more convenient than narrow ones, because many more objects can be processed in the same process time. The ion sources that can produce wide ion beams are now called large area type.

In the case of wide ion beams, it is difficult to separate ions by mass. Wide diameter hinders the mass separation of ion beams. Theoretically, big magnets could separate ions by mass effectively even for wide ion beams. Because of high kinetic energy and wide diameter of ion beams, mass separation has hardly been done for large area type ion sources which generate wide ion beams.

In general, ion beams have energy as large as 10 keV to 200 keV at an outlet of an ion source. In the case of large area type ion sources, the diameter of ion beams is wide. Bending these wide, strong ion beams would require a large, strong magnet with strong magnetic flux. The diameter of the poles of the magnet must be far larger than that of ion beams. Furthermore, the magnet must have an arc shape which coincides with the curvature of bent ion beams.

It is uneasy to manufacture such a huge, strong magnet. It is still difficult to mount the big magnet at the outlet of an ion source.

By these reasons, conventional large area type ion sources have rarely been equipped with mass separation device so far.

Large area type ion sources which generate wide beams are used for finishing, processing or improving objects or for doping objects with impurity. It is preferable that the ions bombarding objects are restricted to a certain kind of ions which have a definite mass. However, various kinds of ions are excited in an ion source. Without a mass separation device, undesirable ions are not eliminated. Such undesirable ions also bombard objects, which would bring about some inconvenience. Therefore, large area type ion sources also require a mass separation device.

However, conventional mass separation devices which would bend the passage of ion beams by a big magnet with a pair of wide pole pieces would be unpractical because of the huge size of the magnet. A purpose of this invention is to provide a large area type ion source with a mass separation device without increasing the size of an ion source. Another purpose of the invention is to provide a large area type ion source with a mass separation device which works under weak magnetic field and low electric field.

This object is achieved by an ion source according to claim 1 or 8 or 15.

This invention proposes an ion source having a mass separation device comprising an ion source chamber having a gas inlet and an outlet and being able to be made vacuum for introducing material gas therein and for exciting the material gas into plasma, a plasma electrode plate with plural holes perforated perpendicularly to a surface mounted at the outlet of the ion source chamber for producing ion beams from the plasma in the ion source chamber, an extraction electrode plate with plural holes corresponding to the holes of the plasma electrode plate mounted next to the plasma electrode plate at the outlet of the ion source chamber for extracting ion beams forward, an acceleration electrode plate with plural holes corresponding to the holes of the extraction electrode plate mounted next to the extraction electrode plate in the outlet of the chamber for accelerating ion beams and a grounded electrode plate with plural holes corresponding to the holes of the acceleration electrode plate mounted next to the acceleration electrode plate in the outlet of the chamber, wherein every hole of the extraction electrode plate is equipped with a Wien filter including a pair of electrodes for generating a static electric field perpendicular to an axial direction of the holes and a pair of magnetic poles for generating a static magnetic field perpendicular both to the axial direction and to the direction of electric field and only such ions with a certain mass that have passed through the holes of the extraction electrode plate can pass through the holes of the next acceleration electrode plate.

A conventional ion source has in general three electrode plates with holes, i.e. a plasma electrode plate, an acceleration electrode plate and a grounded

electrode plate. The plasma electrode plate is biased with high voltage being the same as the voltage of the chamber. The acceleration electrode plate is biased with negative low voltage. The grounded electrode plate is grounded.

The present invention adds an extraction electrode plate and Wien filters mounted to the holes of the extraction electrode plate. Thus, a feature of the invention is the Wien filters of the holes for separating ions by their mass by the actions of electric field and magnetic field which are perpendicular to each other. The Wien filters will separate ions by their mass. A Wien filter is known as a device for separating ions by mass. However, conventional Wien filter was a single, individual device for mass separation of ion beams with high energy. Such a conventional Wien filter used to be mounted at a passage of ion beams which have passed through the last grounded electrode plate.

However, this invention makes use of many Wien filters installed at all the holes of the extraction electrode plate for mass separation of ion beams with low energy before acceleration.

The holes for ion beam passages of four electrode plates, i.e. plasma electrode plate, extraction electrode plate, acceleration electrode plate and grounded electrode plate are perforated at the same positions of the large area type surfaces of the electrode plates. Therefore, a set of four holes of the four electrode plates are aligned along an axial line perpendicular to the plates, because four electrodes are installed in parallel with each other at the outlet of the ion source chamber. However, each diameter of the holes in a set of the electrode plates is not necessarily equal. Therefore, only the ions which have passed through the holes of the extraction electrode plate along the axial direction without being bent by the Wien filters of the holes, can pass through a series of holes of the acceleration electrode plate and the grounded electrode plate. On the contrary, the ions which have passed the holes of the extraction electrode plate with being bent by the Wien filters, cannot pass through the succeeding holes of the acceleration electrode plate and the grounded electrode plate, because they collide with the surface either of the acceleration electrode plate or the grounded electrode plate.

Ions pass through the holes of the extraction electrode plate with the same energy which is equal to the potential difference between the voltage of the plasma electrode plate and the voltage of the extraction electrode plate. Since the ions passing through the holes of the extraction electrode plate have the same kinetic energy, only such ions with a certain mass can pass straight through the holes. The ions which have heavier mass than the predetermined mass will be bent to some direction. The ions which have lighter mass than the predetermined mass will be also bent to the other direction by the Wien filters. Such ion beams with heavier mass or lighter mass cannot pass through the holes of the acceleration electrode plate or the grounded electrode plate.

Every Wien filter generates a static electric field E perpendicular to the axial line of the hole and a static magnetic flux B perpendicular both to the axial line (the direction of the ion movement) and to the electric field. The velocity of an ion is denoted by "w".

The ions which pass straight through the holes have the velocity w which satisfies the equation,

$$Bw = E \quad (1)$$

The energy of ions at the extraction electrode plate is denoted by $qV_{\square}$, where q is electric charge and $V_{\square}$ is the voltage between the plasma electrode plate and the extraction electrode plate. M is mass of the ion. The velocity w of ions is given by

$$w = (2\,q\,V_{\square}/M)^{1/2} \quad (2)$$

Accordingly, in order to separate such ions having a certain mass M from other ions having other mass, the electric field E and the magnetic flux B should be determined to satisfy Eq.(1) and Eq.(2).

This invention provides Wien filters at the extraction electrode plate where the energy of ions is still low. The low energy of ions allows low electric field E of the Wien filters. Low electric field simplifies the structures of the electrode plates and of the supporting insulators. Such simplified Wien filters are easy to produce.

The Wien filter installed at the holes of the extraction electrode plate consists of permanent magnets buried on both sides of the hole and a pair of electrodes. The magnets generate a static magnetic field perpendicular to the axial direction. The electrodes form a static electric field perpendicular both to the axial direction and the magnetic field.

In general, the kinetic energy $qV_{\square}$ of ions is less than 1 keV at the extraction electrode plate. The Wien filters mounted at the holes of the extraction electrode plate separate ions whose energy is less than 1 keV. In many cases, the energy is several hundreds of eV. Low magnetic field and low electric filed are available for mass separation of such ions with low energy. The ions will be accelerated to more than 100 keV by the acceleration electrode plate.

Much stronger electric field and magnetic field would be required for mass-separating the ions with energy of 100 keV by a Wien filter.

The advantage of this invention will be explained. The conventional large area type ion source has no mass separation device. This invention provides a large area type ion source with a mass separation device. The mass separation device prevents impurity ions from being implanted into an object.

Instead of bending wide ion beams as a whole, partial small ion beams passing through a hole are bent independently by a Wien filter installed at the hole. Small magnets and small electrodes are avail-

able. The size of a Wien filter is very small because of low electric field, low magnetic field and small diameters of the partial ion beams. However, since this invention makes use of many Wien filters, many magnets and electrodes are required.

This invention proposes a further improvement of an ion source which has five electrode plates instead of four. A separation electrode plate is added between the extraction electrode plate and the acceleration electrode plate. The separation electrode plate has narrower holes than the acceleration electrode plate to raise the resolution of mass separation.

This invention also proposes a further embodiment which has six electrode plates.

The invention will be more fully understood from the following description given by way of example only with reference to the several figures of the drawings in which,

Fig.1 is a schematic view of an ion source of an embodiment of this invention.

Fig.2 is an enlarged vertical, sectional view near a series of holes of the electrode plates of Fig.1.

Fig.3 is a plan view of a part of an extraction electrode near a hole.

Fig.4 is a schematic view of an ion source of another embodiment of this invention.

Fig.5 is an enlarge, vertical sectional view near two series of holes of the electrode plates of Fig.4.

Fig.6 is a horizontal sectional view of a part of an example of the extraction electrode plate.

Fig.7 is a horizontal sectional view of a part of another example of the extraction electrode plate.

Fig.8 is a horizontal sectional view of a part of third example of the extraction electrode plate.

Fig.9 is a vertical, sectional view of the electrode of third embodiment of this invention.

Fig.10 is a plan view of the extraction electrode of Fig.9.

An ion source introduces material gas into a chamber 6, excites the gas into plasma by electric discharge and pulls ion beams from the plasma by the action of electrode plates.

The electric discharge is either an arc discharge (DC), a glow discharge (DC or AC) or a microwave discharge. In many cases, many permanent magnets are mounted on an outer surface of the chamber in order to form cusp magnetic fields in the chamber.

[EMBODIMENT 1]

Fig.1 shows, as an example, a bucket type ion source having a chamber 6 and a filament 7 for inducing an arc discharge between the chamber (anode) 6 and the filament (cathode) 7 and for exciting material gas into plasma by the arc discharge. Since this invention relates only to an improvement of electrode plates, it is able to be applied to any type of ion sources.

The ion source chamber 6 has a gas inlet 8 for introducing material gas and an outlet for exhausting ion beams. Four electrode plates are mounted at the outlet of the chamber 6. The first is a plasma electrode plate 1. The second is an extraction electrode plate 2. The third is an acceleration electrode plate 4. The fourth is a grounded electrode plate 5. These electrode plates 1, 2, 4 and 5 have many ion holes 11, 12, 14 and 15 perforated along the same axial lines. Ion beams can pass through a series of the ion holes 11, 12, 14 and 15. A three-dimensional coordinate system is defined here to take xy-planes in parallel with the electrode plates 1, 2, 4 and 5. The ion holes 11, 12, 14 and 15 are aligned in parallel with the z-axis. Therefore, only the ion beams which enter the first ion hole 11 and make straight way along the z-direction can pass through all four ion holes 11, 12, 14 and 15.

The plasma electrode plate 1 is biased at the highest voltage. The extraction electrode plate 2 is biased at the second highest voltage. The acceleration electrode plate 4 is biased at a negative voltage. The grounded electrode plate 5 is grounded. A set of the plasma electrode plate 1, the acceleration plate 4 and the grounded electrode plate 5 is the most conventional assembly of electrode plates for ion sources.

However, the extraction electrode plate 2 is novel. Each ion hole 12 of the extraction electrode plate has a Wien filter for mass-separation of ions. This is the most important feature of this invention.

There are many permanent magnets 9 and 10 on the external surface of the chamber 6. The magnets 9 and 10 form cusp magnetic fields in the chamber 6. The cusp magnetic fields prevent plasma 18 from coming into contact with the inner surface of the chamber 6.

The filament 7 is heated by a filament power source 16. Material gas is introduced into the chamber 6 through the gas inlet 8. An arc power source 17 applies positive voltage to the chamber 6 with regard to the filament 7. Thus, a DC voltage is established between the cathode filament 7 and the anode chamber 6. The heated filament 7 emits thermal electrons. The thermal electrons are accelerated by the DC voltage between the filament 7 and the chamber 6. Accelerated electrons collide with neutral gas molecules and excite them into plasma 18. Then an arc discharge is established between the cathode filament 7 and the chamber 6. The material gas is excited into plasma by the DC arc discharge.

A power source 23 biases the plasma electrode plate 1 at positive voltage. A power source 30 biases the chamber 6 further positively to the plasma electrode plate 1. A power source 24 applies a negative voltage to the acceleration electrode plate 4. A power source 19 biases the extraction electrode plate 2 negatively to the plasma electrode plate.

Since the essential feature of this invention is the extraction electrode plate 2 with ion holes 12 having individual Wien filters for mass separation, the ion holes 12 and the Wien filters will be explained by Fig.2 and Fig.3.

A Wien filter comprises a pair of permanent magnets 40 and 41 which face each other with different magnetic poles and a pair of parallel electrodes 42 and 43. The permanent magnets 40 and 41 form a static magnetic field in parallel with y-axis. The parallel electrodes 42 and 43 produce a static electric field in parallel with x-axis.

Four corners of the ion holes have corner pieces 35 which are made from non-magnetic material. In the embodiment, the permanent magnets are rectangular magnets. The direction of magnetism is perpendicular to the vertical line of the extraction electrode plate 2. The direction of magnetism is now denoted by y-direction. The magnets 40 and 41 generate a magnetic field in the y-direction. The parallel electrodes 42 and 43 produce an electric field in the x-direction. Ion beams pass in the z-direction through the ion holes 12.

A three dimensional coordinate system is now defined by taking a central point of the front side of an ion hole 12 of the extraction electrode plate 2 as the origin in order to consider what movement an ion which has passed through the hole 12 will do. A center line l-m is z-axis. The central point of the rear side of the ion hole 12 is denoted by K. The length of the hole 12, i.e. the thickness of the extraction electrode plate 2, is designated by L_m. The central point of the front side of the acceleration electrode plate 4 is denoted by L. D is the diameter of the ion hole 14 of the acceleration electrode plate 4. L_d is the distance between the rear side of the extraction electrode plate 2 and the front side of the acceleration electrode plate 4.

Since a DC voltage is applied between the parallel electrodes 42 and 43, a static electric field E is established in the x-direction. Permanent magnets 40 and 41 generate a static magnetic flux B in the y-direction.

Velocity components of an ion are expressed by a vector (u, v, w). The static electric field is written as (E, 0, 0). The static magnetic flux is given by (0, B, 0). In the ion hole 12, an ion shall follow the equation of motion ;

$$M\,(du/dt) = qE - qwB \quad (3)$$

$$M\,(dv/dt) = 0 \quad (4)$$

$$M\,(dw/dt) = quB \quad (5)$$

A complex variable ζ is defined by $\zeta = u + iw$. Eq. (3) and Eq.(5) can integrally be expressed by,

$$M\,(d\zeta/dt) = qE + iqB\,\zeta \quad (6)$$

where M is the mass of the ion and q is the electric charge of the ion. Solution of Eq.(6) is given by,

$$\zeta = (iE/B) + C\exp(i\omega t) \quad (7)$$

$$\omega = (qB/M) \quad (8)$$

If initial conditions are imposed by $u = u_\square$ and $w = w_\square$ at $t = 0$, the velocity components u and w are,

$$u = u_\square \cos\omega t - \{w_\square - (E/B)\}\sin\omega t \quad (9)$$

$$w = (E/B) + u_\square \sin\omega t + \{w_\square - (E/B)\}\cos\omega t \quad (10)$$

"$x_\square$" denotes x at t = 0. The displacement x is obtained as,

$$x = x_\square + (u_\square/\omega)\sin\omega t - \{w_\square - (E/B)\}(1 - \cos\omega t)/\omega \quad (11)$$

Eq.(9) teaches us that an ion will follow a linear path without being bent in the ion hole 12 under the condition.

$$w_\square = (E/B) \quad (12)$$

This is identical to Eq.(1). Eq.(2) makes the straight-pass condition relevant to the ion energy qEd and the ion mass M.

Substituting $t = L_m/w_\square$, we obtain the velocity u and the displacement x at the outlet ($x = L_m$) of the Wien filter. A dimensionless parameter β is defined by,

$$\beta = \omega L_m/w_\square \quad (13)$$

u and x are written in brief as,

$$u = u_\square \cos\beta - \{w_\square - (E/B)\}\sin\beta \quad (14)$$

$$x = x_\square + (u_\square/\omega)\sin\beta - \{w_\square - (E/B)\}(1 - \cos\beta)/\omega \quad (15)$$

If we wished to obtain rigorous, statistical efficiency of the Wien filter, we should investigate whether an ion having $x = x_\square$ and $u = u_\square$ at $t = 0$ could pass through the next ion hole of the acceleration electrode plate or not, taking the distributions of $x_\square$ and $u_\square$ into account. However, such estimation would be too difficult. For simplicity only the mass dispersion of ion beams having $x_\square = 0$ and $u = 0$ at $t = 0$ were considered. Since ion energy is still low at the extraction electrode plate 2, such assumption can not be so unrealistic.

In brief, approximation of $\sin\beta = \beta$ is now employed, because β is much less than 1 ($0 < \beta << 1$). The displacement of the ion at the front surface of the acceleration electrode plate 4 is now denoted by X.

$$X = -\{w_\square - (E/B)\}(1 - \cos\beta)/\omega - \{w_\square - (E/B)\} + L_d \sin\beta/w_\square \quad (16)$$

$$\fallingdotseq -\{w_\square - (E/B)\}\{(L_d + L_m/2)\,\omega L_m\}/w_\square^2 \quad (17)$$

The ion energy is the same despite the difference of mass, because the energy of acceleration before the extraction electrode plate is the same. Thus, the z-component $w_\square$ of the initial velocity is solely determined by the mass M. Then, such an ion which satisfies the condition $w_\square = E/B$ is designated by $M_\square$. $M_\square$ is the mass of the ions whose beams are required to treat objects. Other ions whose mass is not $M_\square$ should be eliminated before reaching objects. In order to estimate the performance of mass separation, the deviation of an ion whose mass deviates by δM from $M_\square$ ($M = M_\square + \delta M$) at the front surface of the acceleration electrode plate 4 will be now calculated. For such ions, the equation $w_\square = E/B$ does not hold. $w_\square$ deviates from E/B (constant value) by some amount in proportion to mass difference δM.

$$w_\square - (E/B) = \{2qV_\square/(M_\square + \delta M)\}^{1/2} - (2qV_\square/M_\square)^{1/2} \quad (18)$$

$$\fallingdotseq -(2qV_{\square})^{1/2}\delta M/(2M_{\square}^{3/2}) \quad (19)$$

Substituting Eq.(19) into Eq.(17), we obtain the displacement X of the ion.

$$X = (\delta M \omega L_m)(L_d + L_m/2)/(2M_{\square}w_{\square}) \quad (20)$$

Here, the definition of the variables is now recited in order to deter the significance of equations from being ambiguous. δM is the difference of mass, ω is an angular cyclotron frequency of the ion, L_m is the length of the ion hole 12 and L_d is the distance from the rear surface of the extraction electrode plate to the front surface of the acceleration electrode plate. $M_{\square}$ is the standard, reference mass. $w_{\square}$ is an initial velocity of the ion. Eq.(20) teaches that such ions with the mass bigger than $M_{\square}$($\delta M > 0$) will deviate from the axial line to the plus x-direction ($x > 0$) at the acceleration electrode plate 4 and other ions with the mass lighter than $M_{\square}$ ($\delta M < 0$) will deviate from the axial line to the minus x-direction ($x < 0$). The displacement is in proportion to the substantial length ($L_d + L_m/2$) of free flight of ion, in proportion to the length L_m of the Wien filter but in reverse proportion to the mass $M_{\square}$ or the velocity $w_{\square}$.

The diameter of the next ion hole 14 of the acceleration electrode plate 4 is denoted by Δ_x(= D). An ion which has flown along the central line OK through the Wien filter can pass through the hole 14 of the acceleration electrode plate 4, if $|x| < \Delta_x/2$. Since some portions of ion beams flow near the side wall of the filter holes 12, $|x| < \Delta_x$ is the general condition for passing through the ion holes 14 of the acceleration plate 4. Then substitution of x with Δ_x gives us the formula of resolution power of the Wien filter.

$$(M_{\square}/\delta M) = (\omega L_m)(L_d + L_m/2)/(2\Delta_x w_{\square}) \quad (21)$$

Resolution power, electric field or magnetic field will be considered by referring to two examples.

[EXAMPLE 1]

Energy at the extraction electrode plate ... $qV_{\square}$ = 1 keV

Diameter of ion holes of the extraction electrode plate .. Δ_x = 2 mm

Length of ion holes of the extraction electrode plate .. L_m = 20 mm

Distance between the extraction electrode and the acceleration electrode ... L_d = 20 mm

The reference mass $M_{\square}$ is 31. The desired ion is a single-charged phosphorus ion P^+. The initial velocity $w_{\square}$ is calculated as,

$$w_{\square} = 7.86 \times 10^4 \text{ m/sec}$$

These parameters determine the resolution power as a function of magnetic flux

$$M_{\square}/\delta M = 5.9 \times B \quad (22)$$

The relation between E and B is

$$E = 7.86 \times 10^4 B \quad (23)$$

(i) ^{31}P and ^{52}Cr : ^{52}Cr is mixed in the ion beams of ^{31}P. In order to separate ^{52}Cr ions from ^{31}P ions, the resolution power shall be at least

$$M_{\square}/\delta M = 31/(52 - 31) = 1.48 \quad (24)$$

Eq.(22), Eq.(23) and Eq.(24) determine the magnetic flux B and the electric field E for the resolution power.

$$B = 0.25 \text{ (Tesla)} \quad (25)$$

$$E = 1.97 \times 10^4 \text{ V/m} \quad (26)$$

(ii) ^{31}P and $^{28}N_2$: $^{28}N_2$ is mixed in the ion beams of ^{31}P. $^{28}N_2$ is more difficult to separate by mass than ^{52}Cr because of smaller difference of mass. The resolution power shall be at least,

$$M_{\square}/\delta M = 31/(31 - 28) = 10.3 \quad (27)$$

Therefore, Eq.(22), Eq.(23) and Eq.(27) produce

$$B = 1.7 \text{ (Tesla)} \quad (28)$$

$$E = 1.37 \times 10^5 \text{ V/m} \quad (29)$$

[EXAMPLE 2]

Energy at the extraction electrode plate ... $qV_{\square}$ = 100 eV

Diameter of ion holes of the extraction electrode plate .. Δ_x = 2 mm

Length of ion holes of the extraction electrode plate .. L_m = 20 mm

Distance between the extraction electrode and the acceleration electrode ... L_d = 20 mm

The reference mass $M_{\square}$ is 31. The desired ion is also a single-charged phosphorus ion P^+.

$$M_{\square}/\delta M = 18.7 \times B \quad (30)$$

The relation between E and B is

$$E = 2.49 \times 10^4 B \quad (31)$$

(i) ^{31}P and ^{52}Cr : Separation of ^{31}P from ^{52}Cr requires resolution power $M_{\square}/\delta M$ of at least 1.48. Therefore, the magnetic flux B and the electric field E are calculated as

$$B = 0.079 \text{ (Tesla)} \quad (32)$$

$$E = 1.97 \times 10^3 \text{ V/m} \quad (33)$$

(ii) ^{31}P and $^{28}N_2$: Separation of ^{31}P from $^{28}N_2$ corresponds to the resolution power of 10.3.

$$B = 0.551 \text{ (Tesla)} \quad (34)$$

$$E = 13.7 \times 10^7 \text{ V/m} \quad (35)$$

These examples show the strengths of the electric field and the magnetic flux are little. This is mainly because the ion energy is low enough at the Wien filters. This invention separates ions by mass before being accelerated enough. The energy of ions at the extraction electrode plate is less than 1 keV. In usual cases, the energy is as low as 100 eV. Mass separation of ion beams with low energy requires a low magnetic flux and a low electric field.

[EMBODIMENT 2]

EMBODIMENT 1 has drawbacks. The extraction electrode plate 2 is biased with a high positive voltage. The next (acceleration) electrode plate 4 is biased with a negative voltage. The voltage drop between the extraction electrode plate 2 and the accel-

eration electrode plate 4 is considerably large. Thus, the ions which have been accelerated therebetween and have collided with the acceleration electrode plate 2 have a large kinetic energy. For example, the bias of the electrodes plates is assumed to be

plasma electrode plate ... 10 kV
extraction electrode plate ... 9.6 kV
acceleration electrode plate ... - 0.5 kV
grounded electrode plate ... 0 kV

In this case, the ions whose mass is less than $M_{\square}$ (underweight) or more than $M_{\square}$ (overweight) will collide with the acceleration electrode plate with the high kinetic energy of 10.5 keV. The bombardments of overweight or underweight ions generate a lot of secondary electrons from the acceleration electrode plate. The secondary electrons induce a parasitic discharge between the acceleration electrode plate and the extraction electrode plate. The discharge will perturb the biases of the electrode plates, dissipate electric power and excite unnecessary ions between the electrode plates. This is a drawback. Therefore, such an occurrence of parasitic discharge shall be avoided.

Another defect is the low resolution power. The ions are accelerated in the z-direction by the electric field between the extraction electrode plate 2 and the acceleration electrode plate 4. Even off-axis ions which have flown along skew directions will pass through the ion holes 14 of the acceleration electrode plate 4 by the attraction force of the acceleration electrode plate. So, even overweight ions or underweight ions will be able to pass through the ion holes 14. The focussing function of the strong electric field produced between the extraction electrode plate and the acceleration electrode plate deteriorates the resolution power. An embodiment with high resolution power being immune from the occurrence of secondary electrons will now be described.

Embodiment 2 has five electrode plates, i.e. a plasma electrode plate 1, an extraction electrode plate 2, a mass-separation electrode plate 3, an acceleration electrode plate 4 and a grounded electrode plate 5. Fig.4 shows the schematic view of embodiment 2. Fig.5 shows the sectional view of the electrode plates. Fig.6 shows a plan view of the extraction electrode plate. Embodiment 2 has five electrode plates instead of four electrode plates. The mass-separation electrode plate 3 is newly introduced in embodiment 2.

Five electrode plates 1 to 5 are in parallel installed at the outlet of the ion source chamber 6. They have a lot of ion holes perforated perpendicularly to the surface. The ion holes of all electrode plates 1 to 5 are aligned along with parallel axial lines. The newly-introduced mass-separation electrode plate 3 has smaller ion holes than the extraction electrode plate 2. Unlike the acceleration electrode plate 4, the mass-separation electrode plate 3 is applied with a positive high voltage slightly lower than the bias of the extraction electrode plate 2. Thus, ions are not accelerated so fast between the extraction electrode plate 2 and the mass-separation electrode plate 3.

Like embodiment 1, the chamber 6 has an filament 7 which is heated by a filament power source 16. The chamber 6 can be made vacuum by a vacuum pump. Material gas is introduced through a gas inlet 8. Permanent magnets 9 and 10 are installed on the outer wall of the chamber 6 in order to form a cusp magnetic field in the chamber.

The chamber 6 is positively biased by an arc power source 17 with regard to the filament 7. The arc power source 17 induces an arc discharge between the chamber (anode) 6 and the filament (cathode) 7. The DC arc discharge excites the material gas into plasma. Five electrode plates 1 to 5 are mounted at the outlet of the chamber 6. The plasma electrode plate 1 is positively biased by a power source 23. However, the voltage of the plasma electrode plate 1 is slightly lower than that of the chamber 6.

The extraction electrode plate 2 is biased by a power source 19 slightly lower than the plasma electrode plate 1. The extraction electrode plate 2 has a lot of Wien filters at the ion holes. As a Wien filter requires two different voltage levels, two reversely biasing power sources 20 and 21 are provided in common to the Wien filters.

The mass-separation electrode plate 3 is biased slightly lower than the extraction electrode plate 2. The acceleration electrode plates 4 is biased with negative voltage. The grounded electrode plate 5 is grounded (V = 0).

For example, the biases of the electrode plates are settled as ;

plasma electrode plate ... 10 kV
extraction electrode plate ... 9.9 ~ 9.6 kV
mass-separation electrode plate ... 9.7 ~ 8.0 kV
acceleration electrode plate ... -0.5 ~ -1 kV
grounded electrode plate ... 0 V

The ions have low energy and low speed till they have passed through the ion holes of the mass-separation electrode plate 3.The ions are mainly accelerated between the mass-separation electrode plate 3 and the acceleration electrode plate 4.

Each ion hole of every electrode plate is aligned along a central line m - n. The ion holes 12 of the extraction electrode plate 2 are provided with Wien filters. A Wien filter consists of four permanent magnets 28 and a pair of common electrodes 27a and 27b. In Fig.6, the ion holes aligned in y-direction have common electrodes 27a and 27b. Electrode 27b is positively biased by the power source 21. Electrode 27a is negatively biased by the power source 20. Thus, a static electric field E is generated in the x-direction. Two electrodes 27a and 27b belonging to the same

Wien filters are separated in the middle by insulators 29. Neighboring electrodes 27a and 27b belonging to different Wien filters are separated in the middle by another insulator 30. The insulators 29 and 30 effectively prevent the electric field from inducing discharge between the electrodes (27a) and (27b).

Four permanent magnets 28 are aligned in the same direction. They form a magnetic field in the ion holes in the y-direction. The electric field (x-direction) and the magnetic field (y-direction) of the Wien filter give opposite forces to the ions flying in the z-direction. Such an ion with reference mass $M_{\square}$ having a certain velocity $w_{\square} = E/B$ can pass straightly through the Wien filter, because the opposite forces are exactly balanced. Overweight ions with lower speed bend to the direction of the electric field. Underweight ions with higher speed bend to the direction reverse to the electric field. Such bent ion beams 26 collide with the mass-separation electrode plate 3 and lose their energy. Thus, underweight ions and overweight ions are eliminated from the ion beams. The ion holes 13 of the mass-separation electrode plate 3 are smaller than those of the extraction electrode plate 2. Thus, the smaller ion holes 13 are seen behind the bigger ion holes 12 in Fig.6. The smaller ion holes improve the resolution power of the Wien filters. This is one advantage of embodiment 2.

The other advantage is no occurrence of secondary electrons at the mass-separation electrode plate, because the ions have insufficient energy at the mass-separation electrode plate 3 because of the small difference of voltage between the extraction electrode plate 2 and the mass-separation electrode plate 3. Thus, no parasitic discharge occurs between the extraction electrode plate and the mass-separation electrode plate.

[EMBODIMENT 3]

Fig.7 exhibits embodiment 3. Ion holes are disposed at corners of a regular triangle. Electrodes 27 of neighboring Wien filters are unified unlike embodiments 1 and 2. The left electrode is positively biased. The middle electrode 27c is negatively biased. The right electrode 27d is positively biased. Therefore, the direction of the electric field changes in the x-direction periodically. Therefore, the magnetic field must also change in the x-direction. In the first column, the magnetic field is directed to the minus y-direction. In the second column, it is directed to the plus y-direction. Both the electric field and the magnetic field change in x-direction. Embodiment 3 simplifies the structure of electrodes 27 by reducing the number of electrodes to half. In the example, gaps 31 of electrodes are not filled with insulators.

[EMBODIMENT 4]

Fig.8 shows another embodiment. The ion holes are arranged periodically like lattice work. The electrodes 27g are unified with regard to neighboring columns of Wien filters. Thus, the periodicity of the electrodes is twice as long as embodiment 2. The number of permanent magnets is also reduced to half. Two parallel magnets belong to neighboring Wien filters in the same column. The directions of permanent magnets are the same in the Wien filters in the same column. However, the direction of the permanent magnets changes in x-direction. Embodiment 4 can also simplify the structure of electrodes. The directions of the magnetic field and the electric field change in x-direction.

Directions of bending of underweight ions or overweight ions are different in the Wien filters aligned in x-direction.

[EMBODIMENT 5]

Fig.9 and Fig.10 show another embodiment. Like embodiments 3 or 4, the electrodes of neighboring columns of Wien filters are unified. Thus, the directions of the magnetic field of the Wien filters of the same column are the same. However, the directions of the magnetic field change in the neighboring columns, The ion holes of the extraction electrode plate are not circular but square in the embodiment. One set of electrodes is biased at minus 200 V, and the other set of electrodes is biased at plus 200 V. The disposition of the electrodes and the permanent magnets are similar to embodiment 3 shown in Fig.7. However, embodiment 5 has six electrode plates. The electrode plates are a plasma electrode plate 1, a pulling-out electrode plate 51, a filter electrode plate 52, a mass-separation electrode plate 3, an acceleration electrode plate 4 and a grounded electrode plate 5. Namely, the extraction electrode plates 2 of embodiment 1 to 4 has been divided into the pulling-out electrode plate 51 and the filter electrode plate 52. Although the pulling-out electrode plate plays the same role as the extraction electrode plate regarding the electrostatic action to ions, one of the divided electrode plate is called as pulling-out electrode plate in order to avoid confusion. The square ion holes of the filter electrode plates improve the distribution of electric field in the holes. Circular ion holes would disturb the electric field near the electrodes. In order to make a uniform, parallel electric field, the square ion holes are more appropriate than circular ion holes. The other electrode plates, i.e. the plasma electrode plate 1, the pulling-out electrode plate 51, the mass-separation electrode plate 3, the acceleration electrode plate 4 and the grounded electrode plate 5 have circular ion holes in the example. However, the circular ion holes can be replaced by square ion holes.

In the example, the voltages of the electrode plates are ;

plasma electrode plate ... 10 kV
pulling-out electrode plate ... 9 kV
filter electrode plate ... 9 kV
mass-separation electrode plate ... 9 kV
acceleration electrode plate ... -0.2 kV
grounded electrode plate ... 0 V

The biases of the electrodes of the filter electrode plate are +200 V and -200 V. The difference of voltage of the filter electrodes is 400 V. Namely, the voltage of the plus electrodes is 9.2 kV. The voltage of the minus electrodes is 8.8 kV. In the example, three electrode plates, i.e. the pulling out, filter and mass-separation plate have the same voltage. However, slight voltage decrease is also allowable between the pulling-out electrode plate and the filter electrode plate or between the filter electrode plate and the mass-separation electrode plate.

Embodiments 1 to 4 have an unified extraction electrode plate 2. In such a disposal of electrodes, the horizontal electric field induced by the filter electrodes 27a and 27b is likely to disturb the vertical, pulling electric field between the plasma electrode plate 2 and the extraction electrode plate 3 made by the power source 19. The perturbation of the vertical electric field would induce horizontal (x-direction) aberration of ion beams in front of the extraction electrode plate. Since this embodiment has divided the extraction electrode plate into the pulling out electrode plate and the filter electrode plate, no perturbation of vertical electric field occurs as far as the pulling-out electrode plate. Ion beams can be pulled out straightly by the pulling-out electrode plate 51.

This invention has advantages as follows,

(1) So far a large area type ion source has no mass-separation device.

The inventors have provided a large area type ion source with a mass-separation device for the first time.

(2) Since the ion beams pass through multi-type Wien filters before being accelerated, the Wien filters require neither a high electric field nor a high magnetic field. Low electric fields and low magnetic fields make the cost of manufacturing Wien filters cheaper.

(3) Instead of a single big magnet which bends the ion beams in an arc curve, many small Wien filters are used (multi-type Wien filter). Thus, the small size of individual Wien filter enables us further to reduce the electric field and the magnetic field.

(4) Embodiment 2 has furthermore two advantages, i.e. high resolution power and suppression of parasitic discharge.

(5) Embodiment 5 can pull the ion beams in a straight direction perpendicular to the plate by the pulling-out electrode plate, because the extraction electrode plate is divided into the pulling-out electrode plate and the filter electrode plate.

Claims

1. An ion source having a mass-separation device which converts material gas into plasma and exhausts ion beams from the plasma comprising a vacuum chamber having a gas inlet and an ion outlet, a vacuum pump for evacuating the chamber, a discharge device for generating a discharge in the chamber to excite material gas into plasma. a plasma electrode plate having ion holes and being installed at the outlet of the chamber, the plasma elecrtrode plate, in use, being biased at a high positive voltage lower than the voltage of the chamber, an extraction electrode plate having ion holes at corresponding positions and being installed next to the plasma electrode plate, the extraction electrode, in use, being biased at a high positive voltage lower than the voltage of the plasma electrode plate, an acceleration electrode plate having ion holes at corresponding positions and being installed next to the extraction electrode at the outlet of the chamber, the acceleration electrode plate, in use, being biased at a small negative voltage, a grounded electrode plate having ion holes at corresponding positions as the acceleration electrode plate and being installed next to the acceleration electrode plate at the outlet of the chamber, wherein each ion hole of the extraction electrode is provided with a Wien filter including permanent magnets which face each other and have different magnetic poles and are arranged to produce a magnetic field generally perpendicular to the axial direction of the ion holes, and electrodes facing each other and being biased at different voltages for producing an electric field generally perpendicular both to the magnetic field and to the axial direction, the arrangement being such that, in use, ion beams whose mass is equal to a reference mass $M_{\square}$ follow a generally linear path through the Wien filters of the extraction electrode plate by receiving substantially the same but reverse forces from the electric field and the magnetic field, but other ion beams whose mass is not equal to the reference mass $M_{\square}$ follow a curved or non-linear path through the Wien filters by receiving different, reverse forces from the electric field and the magnetic field, and collide with the next acceleration electrode plate.

2. An ion source as claimed in claim 1, wherein each Wien filter of the ion holes of the extraction electrode plate comprises a pair of permanent magnets aligned on opposite sides of the ion hole with

the same direction of the magnetism and a pair of common electrodes aligned on another opposite sides of the holes.

3. An ion source as claimed in claim 1, wherein the difference of voltage between the plasma electrode plate and the extraction electrode plate is less than 1 kV and the kinetic energy of an ion at the Wien filter of the extraction electrode plate is less than 1 keV.

4. An ion source as claimed in claim 3, wherein the discharge device comprises a filament which when heated emits thermal electrons, a DC power source applying positive voltage to the chamber with regard to the filament, so that an arc discharge is induced between the chamber and the filament.

5. An ion source as claimed in claim 3, wherein the chamber has permanent magnets on the outer surface in order to form cusp magnetic field operable to confine the plasma in the chamber.

6. An ion source as claimed in claim 3, wherein the discharge device comprises a microwave oscillator, and a wave guide for guiding microwave from the microwave oscillator into the chamber, the microwave energy introduced into the chamber exciting the material gas into plasma.

7. An ion source as claimed in claim 3, wherein the discharge device comprises a microwave oscillator, a wave guide for guiding microwaves from the microwave oscillator into the chamber and a coil installed around the outer wall of the chamber for making an axial magnetic field, the axial magnetic field being arranged to rotate electrons with the same frequency as the microwave, and the microwave energy exciting the matetial gas into plasma.

8. An ion source having a mass-separation device which converts material gas into plasma and exhausts ion beams from the plasma comprising a vacuum chamber having a gas inlet and an ion outlet, a vacuum pump for evacuating the chamber, a discharge device for generating a discharge in the chamber to excite material gas into plasma, a plasma electrode plate having ion holes and being installed at the outlet of the chamber, the plasma electrode plate, in use, being biased at a high positive voltage slightly lower than that of the chamber, an extraction electrode plate having ion holes at corresponding positions and being installed next to the plasma electrode plate at the outlet of the chamber, the extraction electrode, in use, being biased at a high positive voltage lower than the voltage of the plasma electrode plate, a mass-separation electrode plate having ion holes at corresponding positions and being installed next to the extraction electrode plate, the mass-separation electrode, in use, being biased at a high positive voltage lower than the voltage of the extraction electrode plate, an acceleration electrode plate having ion holes at corresponding positions to the mass-separation electrode, and being installed next to the mass-separation electrode at the outlet of the chamber, the acceleration electrode plate being biased at a small negative voltage and a grounded electrode plate having ion holes at corresponding positions as the acceleration electrode plate and being installed next to the acceleration electrode plate at the outlet of the chamber, wherein each ion hole of the extraction electrode plate is provided with a Wien filter including permanent magnets which face each other and have different magnetic poles and are arranged to produce a magnetic field generally perpendicular to the axial direction of the ion holes, and electrodes facing each other and being biased at different voltages for producing an electric field generally perpendicular both to the magnetic field and to the axial direction, the arrangement being such that, in use, ion beams whose mass is equal to a reference mass $M_{\square}$ follow a generally linear path through the Wien filters of the extraction electrode plate by receiving substantially the same but reverse forces from the electric field and the magnetic field, but the other ion beams whose mass is not equal to the reference mass $M_{\square}$ follow a curved or non-linear path through the Wien filters by receiving different, reverse forces from the electric field and the magnetic field, and collide with the next mass-separation electrode plate.

9. An ion source as claimed in claim 8, wherein each Wien filter of the ion holes of the extraction electrode plate comprises two pairs of permanent magnets aligned on opposite sides of the ion hole with the same direction of magnetism and a pair of common electrodes aligned on the other opposite sides of the hole, the pair of electrodes being separated by an insulator, the electrodes belonging to the neighboring Wien filters in the direction of the electric field being separated by another insulator and the directions of electric field and the magnetic field being the same with regard to all Wien filters.

10. An ion source as claimed in claim 8, wherein each Wien filter of the ion holes of the extraction electrode plate comprises half of two pairs of permanent magnets aligned on opposite sides of the ion

hole with the same direction of magnetism and belonging in common to the neighboring Wien filters and half of a pair of electrodes aligned on opposite sides of the ion holes and belonging in common to all the Wien filters along the line parallel to the magnetic field.

11. An ion source as claimed in claim 9 or 10, wherein the Wien filters are aligned lengthwise and crosswise in the extraction electrode.

12. An ion source as claimed in claim 9, wherein the difference of voltage between the extraction electrode plate and the mass-separation electrode plate is less than 2 kV.

13. An ion source as claimed in claim 12, wherein the difference of voltage between the plasma electrode plate and the extraction electrode plate is less than 1 kV.

14. An ion source as claimed in claim 8, wherein the ion holes of the mass-separation electrode plate are smaller than that of the extraction electrode plate.

15. An ion source having a mass-separation device which converts material gas into plasma and exhausts ion beams from the plasma comprising a vacuum chamber having a gas inlet and an ion outlet, a vacuum pump for evacuating the chamber, a discharge device for generating a discharge in the chamber to excite material gas into plasma, a plasma electrode plate having ion holes and being installed at the outlet of the chamber, the plasma electrode plate, in use, being biased at a high positive voltage lower than the voltage of the chamber, a pulling-out electrode plate having ion holes at positions corresponding to the plasma electrode plate and being installed next to the plasma electrode plate at the outlet of the chamber, the pulling-out electrode, in use, being biased at a high positive voltage lower than the voltage of the chamber, a filter electrode plate having ion holes at positions corresponding to the pulling-out electrode plate and being installed next to the pulling-out electrode plate, the filter electrode plate, in use, being biased at a high positive voltage equal to or lower than the voltage of the pulling-out electrode plate, a mass-separation electrode plate having ion holes at positions corressponding to the filter electrode plate and being installed next to the filter electrode plate at the outlet of the chamber, the mass-separation electrode plate, in use, being biased at a high positive voltage equal or lower than the voltage of the filter electrode, an acceleration electrode having ion holes at positions coresponding to the mass-separation electrode plate and being installed next to the mass-separation electrode plate at the outlet of the chamber, the acceleration electrode plate, in use, being biased at a negative small voltage, and a grounded electrode plate having ion holes at positions corresponding to the acceleration electrode plate and being installed next to the acceleration electrode plate at the outlet of the chamber, wherein each ion hole of the filter electrode is provided with a Wien filter including permanent magnets which face each other and have different magnetic poles and are arranged to produce a magnetic field generally perpendicular to the axial direction of the ion holes, and electrodes facing each other and being biased at different voltages for producing an electric field generally perpendicular both to the magnetic field and to the axial direction, the arrangement being such that, in use, ion beams whose mass is equal to a reference mass $M_\square$ follow a generally linear path through the Wien filters of the filter electrode plate by receiving substantially the same but reverse forces from the electric field and the magnetic field, but other ion beams whose mass is not equal to the reference mass $M_\square$ follow a curved or non-linear path through the Wien filters by receiving different, reverse forces from the electric field and the magnetic field, and collide with the next mass-separation electrode plate.

16. An ion source as claimed in claim 15, wherein the filter electrode plate has square ion holes.

17. An ion source as claimed in claim 15, wherein the difference of voltages between the plasma electrode and the filter electrode plate is less than 2 kV.

18. An ion source as claimed in claim 17, wherein the difference of voltages between the filter electrode plate and the mass-separation electrode plate is less than 2kV.

Patentansprüche

1. Ionenquelle mit einer Massenseparierereinrichtung, die Materialgas in Plasma umwandelt und Ionenstrahlen aus dem Plasma austreten läßt, mit einer Vakuumkammer, die einen Gaseinlaß und einen Ionenauslaß aufweist, einer Vakuumpumpe zum Evakuieren der Kammer, einer Entladungseinrichtung zum Erzeugen einer Entladung in der Kammer, um das Materialgas zu Plasma anzuregen, einer Plasmaelektrodenplatte mit Ionenlöchern, installiert am Auslaß der Kammer, wobei die Plasmaelektrodenplatte im Betrieb auf eine hohe positive

Spannung vorgespannt wird, die unter der Spannung der Kammer liegt, einer Abziehelektrodenplatte mit Ionenlöchern an entsprechenden Stellen, installiert in der Nachbarschaft der Plasmaelektrodenplatte, wobei die Extrahierelektrode im Betrieb auf eine hohe positive Spannung vorgespannt ist, die unterhalb der Spannung der Plasmaelektrodenplatte liegt, einer Beschleunigungselektrodenplatte mit Ionenlöchern an entsprechenden Stellen, installiert in der Nachbarschaft der Extrahierelektrode am Auslaß der Kammer, wobei die Beschleunigungselektrodenplatte im Betrieb auf eine geringe negative Spannung vorgespannt ist, eine geerdete Elektrodenplatte mit Ionenlöchern an entsprechenden Stellen, die die Beschleunigungselektrodenplatte bildet und installiert in der Nachbarschaft der Beschleunigungselektrodenplatte an dem Auslaß der Kammer, wobei jedes Ionenloch der Extrahierelektrode mit einem Wien-Filter ausgestattet ist, welches Permanentmagneten enthält, die einander gegenüberliegen und unterschiedliche Magnetpole besitzen und so angeordnet sind, daß sie ein Magnetfeld etwa senkrecht zur axialen Richtung der Ionenlöcher erzeugen, und das Elektroden enthält, die einander gegenüberliegen und auf unterschiedliche Spannungen vorgespannt sind, um ein elektrisches Feld etwa senkrecht sowohl zu dem magnetischen Feld als auch zu der axialen Richtung zu erzeugen, wobei die Anordnung derart ausgestaltet ist, daß im Betrieb Ionenstrahlen, deren Masse gleich einer Referenzmasse M_0 ist, einem etwa geradlinigen Weg durch die Wien-Filter der Extrahierelektrodenplatte folgen, indem sie etwa die gleichen, jedoch umgekehrten Kräfte aus dem elektrischen Feld und dem magnetischen Feld aufnehmen, während andere Ionenstrahlen, deren Masse nicht der Referenzmasse M_0 gleicht, einem gekrümmten, oder nicht-linearen Weg durch die Wien-Filter folgen, indem sie andere, umgekehrte Kräfte aus dem elektrischen Feld und dem magnetischen Feld aufnehmen, und mit der benachbarten Beschleunigungselektrodenplatte zusammenprallen.

2. Ionenquelle nach Anspruch 1, bei der jedes Wien-Filter der Ionenlöcher der Extrahierelektrodenplatte ein Paar Permanentmagneten aufweist, die aufeinander gegenüberliegenden Seiten des Ionenlochs in der gleichen Richtung der Magnetisierung angeordnet sind, und ein Paar gemeinsamer Elektroden aufweist, die aufeinander entgegengesetzten Seiten der Löcher ausgerichtet sind.

3. Ionenquelle nach Anspruch 1, bei der die Spannungsdifferenz zwischen der Plasmaelektrodenplatte und der Extrahierelektrodenplatte weniger als 1 kV beträgt, und die kinetische Energie eines Ions an dem Wien-Filter der Extrahierelektrodenplatte weniger als 1 keV beträgt.

4. Ionenquelle nach Anspruch 3, bei der die Entladungseinrichtung ein Filament aufweist, das im aufgeheizten Zustand thermische Elektronen emittiert, eine Gleichspannungsquelle besitzt, die eine positive Spannung an die Kammer in bezug auf das Filament legt, so daß eine Porenentladung zwischen Kammer und Filamant induziert wird.

5. Ionenquelle nach Anspruch 3, bei der die Kammer Permanentmagnete auf der Außenfläche aufweist, um ein Spitzenmagnetfeld zu bilden, welches betreibbar ist, um das Plasma in der Kammer einzugrenzen.

6. Ionenquelle nach Anspruch 3, bei der die Entladungseinrichtung einen Mikrowellenoszillator und einen Wellenleiter zum Leiten der Mikrowellen von dem Mikrowellenoszillator in die Kammer aufweist, wobei die in die Kammer eingeleitete Mikrowellenenergie das Materialgas zu Plasma erregt.

7. Ionenquelle nach Anspruch 3, bei der die Entladungseinrichtung einen Mikrowellenoszillator, einen Wellenleiter zum Leiten von Mikrowellen aus dem Mikrowellenoszillator in die Kammer und eine um die Außenwand der Kammer herum installierte Spule zur Bildung eines axialen Magnetfelds aufweist, wobei das axiale Magnetfeld so angeordnet ist, daß es Elektronen gleicher Frequenz wie die Mikrowelle dreht und wobei die Mikrowellenenergie das Materialgas zu Plasma erregt.

8. Ionenquelle mit einer Massenseparierenrichtung, die Materialgas in Plasma umwandelt und Ionenstrahlen aus dem Plasma austreten läßt, umfassend eine Vakuumkammer mit einem Gaseinlaß und einem Ionenauslaß, einer Vakuumpumpe zum Evakuieren der Kammer, einer Entladungseinrichtung zum Erzeugen einer Entladung in der Kammer, um Materialgas zu Plasma zu erregen, einer Plasmaelektrodenplatte mit Ionenlöchern, installiert am Auslaß der Kammer, wobei die Plasmaelektrodenplatte in Betrieb auf eine hohe positive Spannung vorgespannt ist, die etwas unterhalb derjenigen der Kammer liegt, einer Extrahierelektrodenplatte mit Ionenlöchern an entsprechenden Stellen und installiert in der Nachbarschaft der Plasmaelektrodenplatte am Auslaß der Kammer, wobei die Extrahierelektrode in Be-

trieb auf eine hohe positive Spannung vorgespannt ist, die unterhalb der Spannung der Plasmaelektrodenplatte liegt, einer Massenseparier- elektrodenplatte mit Ionenlöchern an entsprechenden Stellen und installiert in der Nachbarschaft der Extrahierelektrodenplatte, wobei die Massenseparierelektrode im Betrieb auf eine hohe positive Spannung vorgespannt ist, die geringer ist als die Spannung der Extrahierelektrodenplatte, einer Beschleunigungselektrodenplatte mit Ionenlöchern an entsprechenden Stellen wie die Massenseparierelektrode, und in der Nachbarschaft der Massenseparierelektrode am Auslaß der Kammer installiert, wobei die Beschleunigungselektrodenplatte auf eine kleine negative Spannung vorgespannt ist, und einer geerdeten Elektrodenplatte mit Ionenlöchern an entsprechenden Stellen wie die Beschleunigungselektrodenplatte und in der Nachbarschaft der Beschleunigungselektrodenplatte am Auslaß der Kammer installiert, wobei jedes Ionenloch der Extrahierelektrodenplatte mit einem WienFilter ausgestattet ist, welches Permanentmagneten, die einander gegenüberliegen und verschiedene Magnetpole aufweisen sowie angeordnet sind zum Erzeugen eines etwa senkrecht zu der axialen Richtung der Ionenlöcher verlaufenden Magnetfelds, und Elektroden aufweist, die einander gegenüberliegen und auf unterschiedliche Spannungen vorgespannt sind, um ein elektrisches Feld etwa senkrecht sowohl zu dem Magnetfeld als auch zu der axialen Richtung zu erzeugen, wobei die Anordnung derart gestaltet ist, daß im Betrieb solche Ionenstrahlen, deren Masse gleich einer Referenzmasse M_0 ist, einem etwa geradlinigen Weg durch die Wien-Filter der Extrahierelektrodenplatte folgen, indem sie etwa die gleichen, jedoch entgegengesetzten Kräfte aus dem elektrischen Feld und dem Magnetfeld aufnehmen, während die anderen Ionenstrahlen, der Masse nicht der Referenzmasse M_0 gleicht, einem gekrümmten oder nicht-linearen Weg durch die Wien-Filter folgen, indem sie unterschiedliche, entgegengesetzte Kräfte aus dem elektrischen Feld und dem Magnetfeld aufnehmen, und mit der nächstgelegenen Massenseparierelektrodenplatte kollidieren.

9. Ionenquelle nach Anspruch 8, bei der jedes Wien-Filter der Ionenlöcher der Extrahierelektrodenplatte zwei Paare von Permanentmagneten aufweist, die auf entgegengesetzten Seiten des Ionenlochs mit gleicher Magnetisierungsrichtung ausgerichtet sind, und ein Paar gemeinsamer Elektroden aufweist, die an den anderen entgegengesetzten Seiten des Lochs ausgerichtet sind, wobei das Paar von Elektroden durch einen Isolator getrennt ist, die Elektroden, die zu den benachbarten Wien-Filtern in Richtung des elektrischen Feldes gehören, von einem weiteren Isolator getrennt sind, und die Richtungen des elektrischen Feldes und des Magnetfeldes in bezug auf sämtliche Wien-Filter die gleichen sind.

10. Ionenquelle nach Anspruch 8, bei der jedes Wien-Filter der Ionenlöcher der Extrahierelektrodenplatte die Hälfte von zwei Paaren von Permanentmagneten ausgerichtet auf entgegengesetzten Seiten des Ionenlochs mit gleicher Magnetisierungsrichtung und gemeinsam zugehörig zu den benachbarten Wien-Filtern aufweist, und die Hälfte eines Paares von Elektroden aufweist, die auf entgegengesetzten Seiten der Ionenlöcher ausgerichtet sind und gemeinsam zu sämtlichen Wien-Filtern entlang der Linie parallel zu dem Magnetfeld gehören.

11. Ionenquelle nach Anspruch 9 oder 10, bei der die Wien-Filter in Längsrichtung und kreuzweise in der Extrahierelektrode ausgerichtet sind.

12. Ionenquelle nach Anspruch 9, bei der die Spannungsdifferenz zwischen der Extrahierelektrodenplatte und der Masseseparierelektrodenplatte weniger als 2 kV beträgt.

13. Ionenquelle nach Anspruch 12, bei der die Spannungsdifferenz zwischen der Plasmaelektrodenplatte und der Extrahierelektrodenplatte weniger als 1 kV beträgt.

14. Ionenquelle nach Anspruch 8, bei der die Ionenlöcher der Masseseparierelektrodenplatte kleiner sind als diejenigen der Extrahierelektrodenplatte.

15. Ionenquelle mit einer Massensepariereinrichtung, die ein Materialgas in Plasma umwandelt und Ionenstrahlen aus dem Plasma austreten läßt, umfassend eine Vakuumkammer mit einem Gaseinlaß und einem Ionenauslaß, einer Vakuumpumpe zum Evakuieren der Kammer, einer Entladungseinrichtung zum Erzeugen einer Entladung in der Kammer, um Materialgas zu Plasma anzuregen, einer Plasmaelektrodenplatte mit Ionenlöchern, installiert am Auslaß der Kammer, wobei die Plasmaelektrodenplatte im Betrieb auf eine hohe positive Spannung vorgespannt ist, die geringer ist als die Spannung der Kammer, einer Abziehelektrodenplatte mit Ionenlöchern an Stellen entsprechend der Plasmaelektrodenplatte, und installiert in der Nähe der Plasmaelektrodenplatte am Auslaß der Kammer, wobei die Abziehelektrode im Betrieb auf eine hohe positive Spannung vorgespannt ist, die geringer ist als die Spannung der Kammer, einer Filterelektrodenplatte mit Io-

nenlöchern an Stellen entsprechend der Abziehelektrodenplatte, und installiert in der Nachbarschaft der Abziehelektrodenplatte, wobei die Filterelektrodenplatte im Betrieb auf eine hohe positive Spannung gleich der oder geringer als die Spannung der Abziehelektrodenplatte vorgespannt ist, einer Massenseparierelektrodenplatte mit Ionenlöchern an Stellen entsprechend der Filterelektrodenplatte und installiert in der Nachbarschaft der Filterelektrodenplatte am Auslaß der Kammer, wobei die Massenseparierelektrodenplatte im Betrieb auf eine hohe positive Spannung gleich der oder geringer als die Spannnung der Filterelektrode vorgespannt ist, einer Beschleunigungselektrode mit Ionenlöchern an Stellen entsprechend der Massenseparierelektrodenplatte und angeordnet in der Nachbarschaft der Massenseparierelektrodenplatte an dem Auslaß der Kammer, wobei die Beschleunigungselektroden-platte im Betrieb auf eine negative kleine Spannung vorgespannt ist, und einer geerdeten Elektrodenplatte mit Ionenlöchern an Stellen entsprechend der Beschleunigungselektrodenplatte und installiert in der Nachbarschaft der Beschleunigungselektrodenplatte am Auslaß der Kammer, wobei jedes Ionenloch der Filterelektrode mit einem Wien-Filter ausgestattet ist, welches Permanentmagneten enthält, die einander gegenüberliegen und unterschiedliche Magnetpole aufweisen und angeordnet sind zum Erzeugen eines Magnetfelds etwa senkrecht zu der axialen Richtung der Ionenlöcher, und Elektroden aufweist, die einander gegenüberliegen und auf unterschiedliche Spannungen vorgespannt sind, um ein elektrisches Feld etwa senkrecht sowohl zu dem Magnetfeld als auch zu der axialen Richtung zu erzeugen, wobei die Anordnung derart getroffen ist, daß im Betrieb Ionenstrahlen, deren Masse einer Referenzmasse M_0 gleicht, einem geradlinigen Weg durch die Wien-Filter der Filterelektrodenplatte folgen, indem sie im wesentlichen die gleichen jedoch entgegengesetzten Kräfte aus dem elektrischen Feld und dem Magnetfeld aufnehmen, während andere Ionenstrahlen, deren Masse nicht der Referenzmasse M_0 gleicht, einem gekrümmten oder nichtlinearen Weg durch die Wien-Filter folgen, indem sie unterschiedliche, entgegengesetzte Kräfte aus dem elektrischen Feld und dem Magnetfeld aufnehmen, und die mit der nächstgelegenen Massenseparierelektrodenplatte kollidieren.

16. Ionenquelle nach Anspruch 15, bei der die Filterelektrodenplatte quadratische Ionenlöcher besitzt.

17. Ionenquelle nach Anspruch 15, bei der die Spannungsdifferenz zwischen Plasmaelektrode und Filterelektrodenplatte geringer als 2 kV ist.

18. Ionenquelle nach Anspruch 17, bei der die Spannungsdifferenz zwischen der Filterelektrodenplatte und der Masseseparierelektrodenplatte weniger als 2 kV beträgt.

Revendications

1. Une source d'ions présentant un dispositif de séparation de masse qui convertit une matière gazeuse en plasma et libère des faisceaux ioniques du plasma, comprenant une chambre à vide présentant une entrée des gaz et une sortie des ions, une pompe à vide pour faire le vide dans la chambre, un dispositif à décharge pour produire une décharge dans la chambre afin d'exciter la matière gazeuse et former un plasma, une plaque formant électrode à plasma présentant des trous d'ions et étant placée à la sortie de la chambre, la plaque formant électrode à plasma étant, en service, polarisée à une haute tension positive inférieure à la tension de la chambre, une plaque formant électrode d'extraction présentant des trous d'ions à des positions correspondantes et étant placée tout près de la plaque formant électrode à plasma, l'électrode d'extraction étant, en service, polarisée à une haute tension positive inférieure à la tension de la plaque formant électrode à plasma, une plaque formant électrode d'accélération présentant des trous d'ions à des positions correspondantes et étant placée tout près de l'électrode d'extraction à la sortie de la chambre, la plaque formant électrode d'accélération étant, en service, polarisée à une faible tension négative, une plaque formant électrode à la masse présentant des trous d'ions à des positions correspondant à la plaque formant électrode d'accélération et étant placée tout près de la plaque formant électrode d'accélération à la sortie de la chambre, dans laquelle chaque trou d'ions de l'électrode d'extraction présente un filtre de Wien comprenant des aimants permanents se faisant mutuellement face et présentant différents pôles magnétiques en étant prévus pour produire un champ magnétique généralement perpendiculaire à la direction axiale des trous d'ions, et des électrodes se faisant mutuellement face et étant polarisées à des tensions différentes pour produire un champ électrique généralement perpendiculaire à la fois au champ magnétique et à la direction axiale, la disposition étant telle que, en service, des faisceaux d'ions dont la masse est égale à une masse de référence M_0 suivent une trajectoire généralement linéaire à travers les filtres de Wien de la plaque formant

électrode d'extraction en recevant, du champ électrique et du champ magnétique, des forces sensiblement égales mais opposées, mais d'autres faisceaux d'ions dont la masse n'est pas égale à la masse de référence $M_{\square}$ suivent une trajectoire courbe ou non linéaire à travers les filtres de Wien en recevant, du champ électrique et du champ magnétique, des forces différentes et opposées, et viennent heurter la plaque formant électrode d'accélération suivante.

2. Une source d'ions telle que revendiquée à la revendication 1, dans laquelle chaque filtre de Wien des trous d'ions de la plaque formant électrode d'extraction comprend une paire d'aimants permanents alignés sur des côtés opposés du trou d'ions avec la même direction de magnétisme et une paire d'électrodes communes alignées sur les autres côtés opposés des trous.

3. Une source d'ions telle que revendiquée à la revendication 1, dans laquelle la différence de tension entre la plaque formant électrode de plasma et la plaque formant électrode d'extraction est inférieure à 1 kV et l'énergie cinétique d'un ion au niveau du filtre de Wien de la plaque formant électrode d'extraction est inférieure à 1 keV.

4. Une source d'ions telle que revendiquée à la revendication 3, dans laquelle le dispositif à décharge comprend un filament qui, quand il est chauffé, émet des électrons thermiques, une source d'énergie à courant continu appliquant une tension positive à la chambre par rapport au filament, de sorte qu'une décharge d'arc est produite entre la chambre et le filament.

5. Une source d'ions telle que revendiquée à la revendication 3, dans laquelle la chambre présente des aimants permanents sur la surface externe de manière à former un champ magnétique à point de rebroussement agissant pour enfermer le plasma dans la chambre.

6. Une source d'ions telle que revendiquée à la revendication 3, dans laquelle le dispositif à décharge comprend un oscillateur à micro-ondes et un guide d'ondes pour guider les micro-ondes de l'oscillateur à micro-ondes dans la chambre, l'énergie des micro-ondes introduite dans la chambre excitant la matière gazeuse pour former un plasma.

7. Une source d'ions telle que revendiquée à la revendication 3, dans laquelle le dispositif à décharge comprend un oscillateur à micro-ondes, un guide d'ondes pour guider les micro-ondes de l'oscillateur à micro-ondes dans la chambre et une bobine placée autour de la paroi externe de la chambre pour former un champ magnétique axial, le champ magnétique axial étant prévu pour faire tourner des électrons avec la même fréquence que les micro-ondes, et l'énergie des microondes excitant la matière gazeuse pour former un plasma.

8. Une source d'ions présentant un dispositif de séparation de masse qui convertit une matière gazeuse en plasma et libère des faisceaux ioniques du plasma, comprenant une chambre à vide présentant une entrée des gaz et une sortie des ions, une pompe à vide pour faire le vide dans la chambre, un dispositif à décharge pour produire une décharge dans la chambre afin d'exciter la matière gazeuse et former un plasma, une plaque formant électrode à plasma présentant des trous d'ions et étant placée à la sortie de la chambre, la plaque formant électrode à plasma étant, en service, polarisée à une haute tension positive légèrement inférieure à celle de la chambre, une plaque formant électrode d'extraction présentant des trous d'ions à des positions correspondantes et étant placée tout près de la plaque formant électrode à plasma à la sortie de la chambre, l'électrode d'extraction étant, en service, polarisée à une haute tension positive inférieure à la tension de la plaque formant électrode à plasma, une plaque formant électrode de séparation de masse présentant des trous d'ions à des positions correspondantes et étant placée tout près de la plaque formant électrode d'extraction, l'électrode de séparation de masse étant, en service, polarisée à une haute tension positive inférieure à la tension de la plaque formant électrode d'extraction, une plaque formant électrode d'accélération présentant des trous d'ions à des positions correspondant à l'électrode de séparation de masse, et étant placée tout près de l'électrode de séparation de masse à la sortie de la chambre, la plaque formant électrode d'accélération étant polarisée à une faible tension négative et une plaque formant électrode à la masse présentant des trous d'ions à des positions correspondant à la plaque formant électrode d'accélération et étant placée tout près de la plaque formant électrode d'accélération à la sortie de la chambre, dans laquelle chaque trou d'ions de la plaque formant électrode d'extraction présente un filtre de Wien comprenant des aimants permanents se faisant mutuellement face et présentant des pôles magnétiques différents en étant prévus pour produire un champ magnétique généralement perpendiculaire à la direction axiale des trous d'ions, et des électrodes se faisant mutuellement face et étant polarisées à des tensions différentes pour produire un champ électrique généralement per-

pendiculaire à la fois au champ magnétique et à la direction axiale, la disposition étant telle que, en service, des faisceaux d'ions dont la masse est égale à une masse de référence $M_{\square}$ suivent une trajectoire généralement linéaire à travers les filtres de Wien de la plaque formant électrode d'extraction en recevant, du champ électrique et du champ magnétique, des forces sensiblement égales mais opposées, mais les autres faisceaux d'ions dont la masse n'est pas égale à la masse de référence $M_{\square}$ suivent une trajectoire courbe ou non linéaire à travers les filtres de Wien en recevant, du champ électrique et du champ magnétique, des forces différentes et opposées, et viennent heurter la plaque formant électrode de séparation de masse suivante.

9. Une source d'ions telle que revendiquée à la revendication 8, dans laquelle chaque filtre de Wien des trous d'ions de la plaque formant électrode d'extraction comprend deux paires d'aimants permanents alignés sur des côtés opposés du trou d'ions avec la même direction de magnétisme et une paire d'électrodes communes alignées sur les autres côtés opposés du trou, la paire d'électrodes étant séparée par un isolant, les électrodes appartenant aux filtres de Wien voisins dans la direction du champ électrique étant séparées par un autre isolant, et les directions du champ électrique et du champ magnétique étant les mêmes en ce qui concerne tous les filtres de Wien.

10. Une source d'ions telle que revendiquée à la revendication 8, dans laquelle chaque filtre de Wien des trous d'ions de la plaque formant électrode d'extraction comprend la moitié de deux paires d'aimants permanents alignés sur des côtés opposés du trou d'ions avec la même direction de magnétisme et appartenant en commun aux filtres de Wien voisins et la moitié d'une paire d'électrodes alignées sur des côtés opposés des trous d'ions et appartenant en commun à tous les filtres de Wien le long de la ligne parallèle au champ magnétique.

11. Une source d'ions telle que revendiquée à la revendication 9 ou 10, dans laquelle les filtres de Wien sont alignés longitudinalement et transversalement dans l'électrode d'extraction.

12. Une source d'ions telle que revendiquée à la revendication 9, dans laquelle la différence de tension entre la plaque formant électrode d'extraction et la plaque formant électrode de séparation de masse est inférieure à 2 kV.

13. Une source d'ions telle que revendiquée à la revendication 12, dans laquelle la différence de tension entre la plaque formant électrode à plasma et la plaque formant électrode d'extraction est inférieure à 1 kV.

14. Une source d'ions telle que revendiquée à la revendication 8, dans laquelle les trous d'ions de la plaque formant électrode de séparation de masse sont plus petits que ceux de la plaque formant électrode d'extraction.

15. Une source d'ions présentant un dispositif de séparation de masse qui convertit une matière gazeuse en plasma et libère des faisceaux ioniques du plasma, comprenant une chambre à vide présentant une entrée des gaz et une sortie des ions, une pompe à vide pour faire le vide dans la chambre, un dispositif à décharge pour produire une décharge dans la chambre afin d'exciter la matière gazeuse et former un plasma, une plaque formant électrode à plasma présentant des trous d'ions et étant placée à la sortie de la chambre, la plaque formant électrode à plasma étant, en service, polarisée à une haute tension positive inférieure à la tension de la chambre, une plaque formant électrode d'extraction présentant des trous d'ions à des positions correspondant à la plaque formant électrode à plasma et étant placée tout près de la plaque formant électrode à plasma à la sortie de la chambre, l'électrode d'extraction étant, en service, polarisée à une haute tension positive inférieure à la tension de la chambre, une plaque formant électrode de filtrage présentant des trous d'ions à des positions correspondant à la plaque formant électrode d'extraction et étant placée tout près de la plaque formant électrode d'extraction, la plaque formant électrode de filtrage étant, en service, polarisée à une haute tension positive égale ou inférieure à la tension de la plaque formant électrode d'extraction, une plaque formant électrode de séparation de masse présentant des trous d'ions à des positions correspondant à la plaque formant électrode de filtrage et étant placée tout près de la plaque formant électrode de filtrage à la sortie de la chambre, la plaque formant électrode de séparation de masse étant, en service, polarisée à une haute tension positive égale ou inférieure à la tension de l'électrode de filtrage, une électrode d'accélération présentant des trous d'ions à des positions correspondant à la plaque formant électrode de séparation de masse et étant placée tout près de la plaque formant électrode de séparation de masse à la sortie de la chambre, la plaque formant électrode d'accélération étant, en service, polarisée à une faible tension négative, et une plaque formant électrode à la masse présentant des trous d'ions à des positions corres-

pondant à la plaque formant électrode d'accélération et étant placée tout près de la plaque formant électrode d'accélération à la sortie de la chambre, dans laquelle chaque trou d'ions de l 'électrode de filtrage présente un filtre de Wien comprenant des aimants permanents qui se font mutuellement face et présentent des pôles magnétiques différents en étant prévus pour produire un champ magnétique généralement perpendiculaire à la direction axiale des trous d'ions, et des électrodes se faisant mutuellement face et étant polarisées à des tensions différentes pour produire un champ électrique généralement perpendiculaire à la fois au champ magnétique et à la direction axiale, la disposition étant telle que, en service, des faisceaux d'ions dont la masse est égale à une masse de référence $M_{\square}$ suivent une trajectoire généralement linéaire à travers les filtres de Wien de la plaque formant électrode de filtrage en recevant, du champ électrique et du champ magnétique, des forces sensiblement égales mais opposées, mais d'autres faisceaux d'ions dont la masse n'est pas égale à la masse de référence $M_{\square}$ suivent une trajectoire courbe ou non linéaire à travers les filtres de Wien en recevant, du champ électrique et du champ magnétique, des forces différentes mais opposées, et viennent heurter la plaque formant électrode de séparation de masse suivante.

16. Une source d'ions telle que revendiquée à la revendication 15, dans laquelle la plaque formant électrode de filtrage présente des trous d'ions carrés.

17. Une source d'ions telle que revendiquée à la revendication 15, dans laquelle la différence de tension entre la plaque formant électrode de plasma et la plaque formant électrode de filtrage est inférieure à 2 kV.

18. Une source d'ions telle que revendiquée à la revendication 17, dans laquelle la différence de tension entre la plaque formant électrode de filtrage et la plaque formant électrode de séparation de masse est inférieure à 2 kV.

FIG. 1

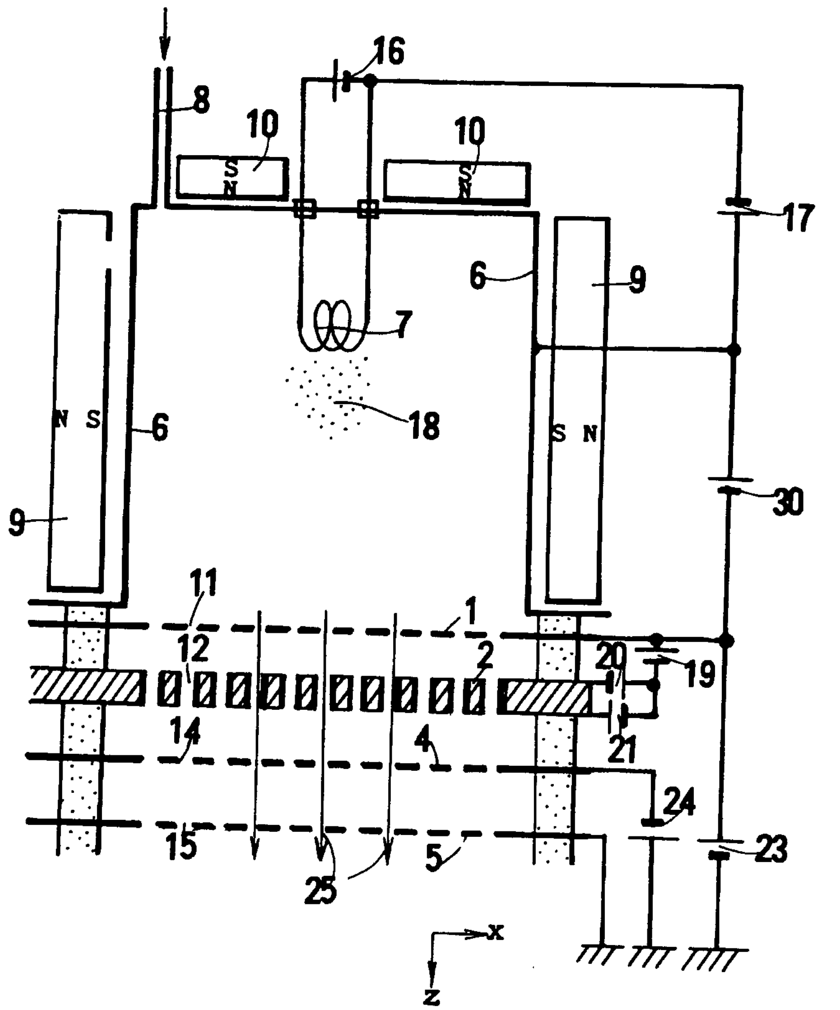


FIG. 2

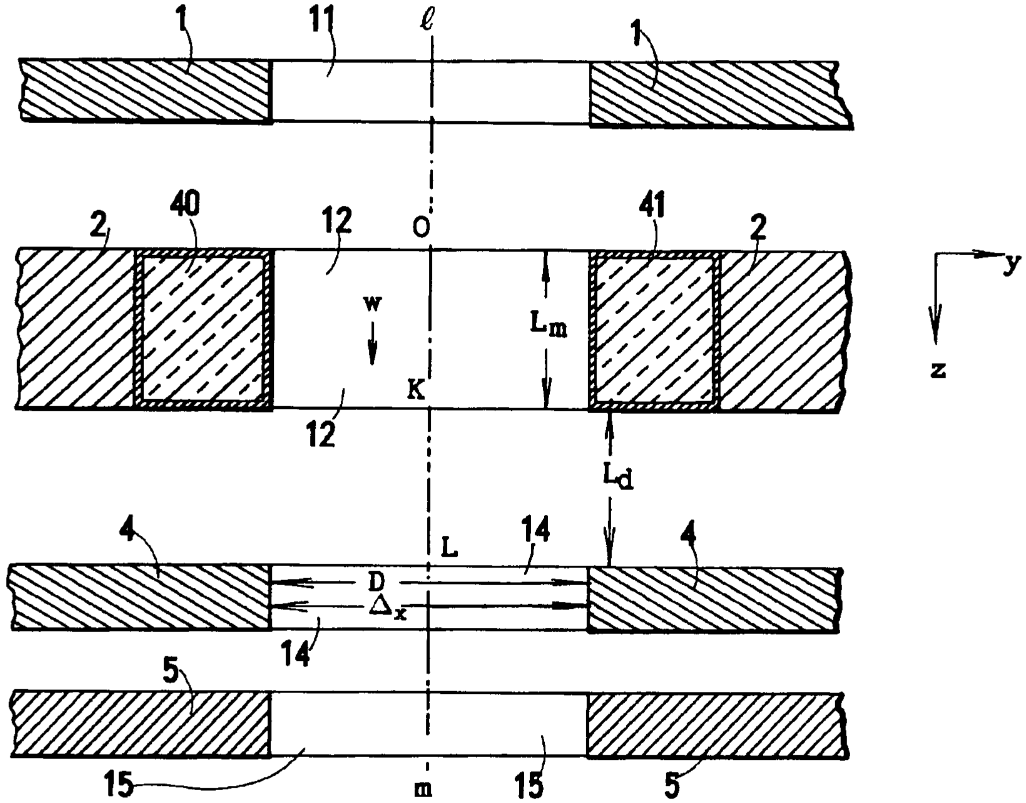

1
11
ℓ
1
2
40
12
O
41
2
y
z
w
Lm
K
12
Ld
4
L
14
4
D
Δx
14
5
15
m
15
5

FIG. 3

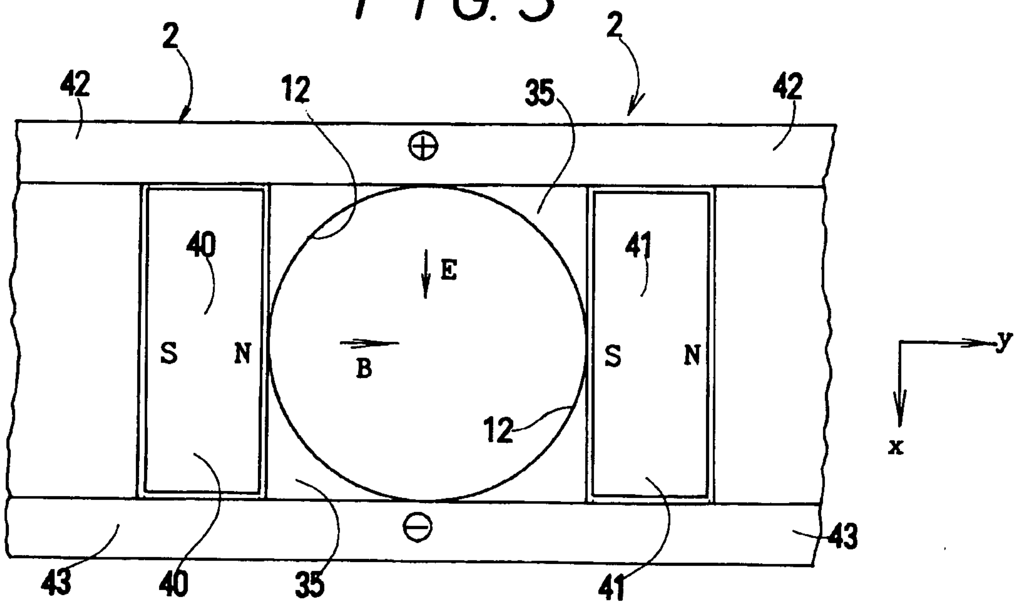
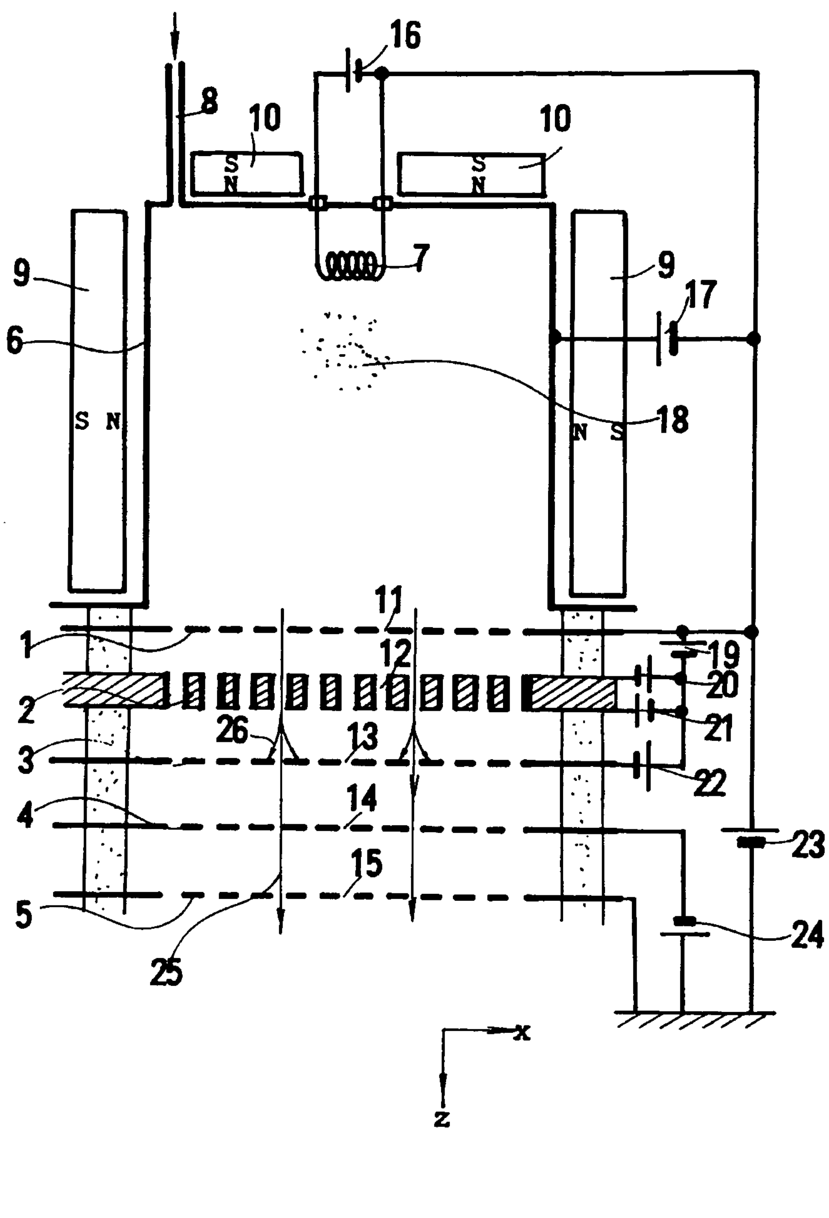

2
2
42
12
35
42
⊕
40
E
41
S
N
B
S
N
y
x
12
⊖
43
40
35
41
43

FIG. 4



8
16
10
10
S
N
S
N
9
9
7
17
6
S N
N S
18
11
1
12
19
20
2
21
26
13
3
22
14
4
23
15
5
24
25
x
z

FIG. 5

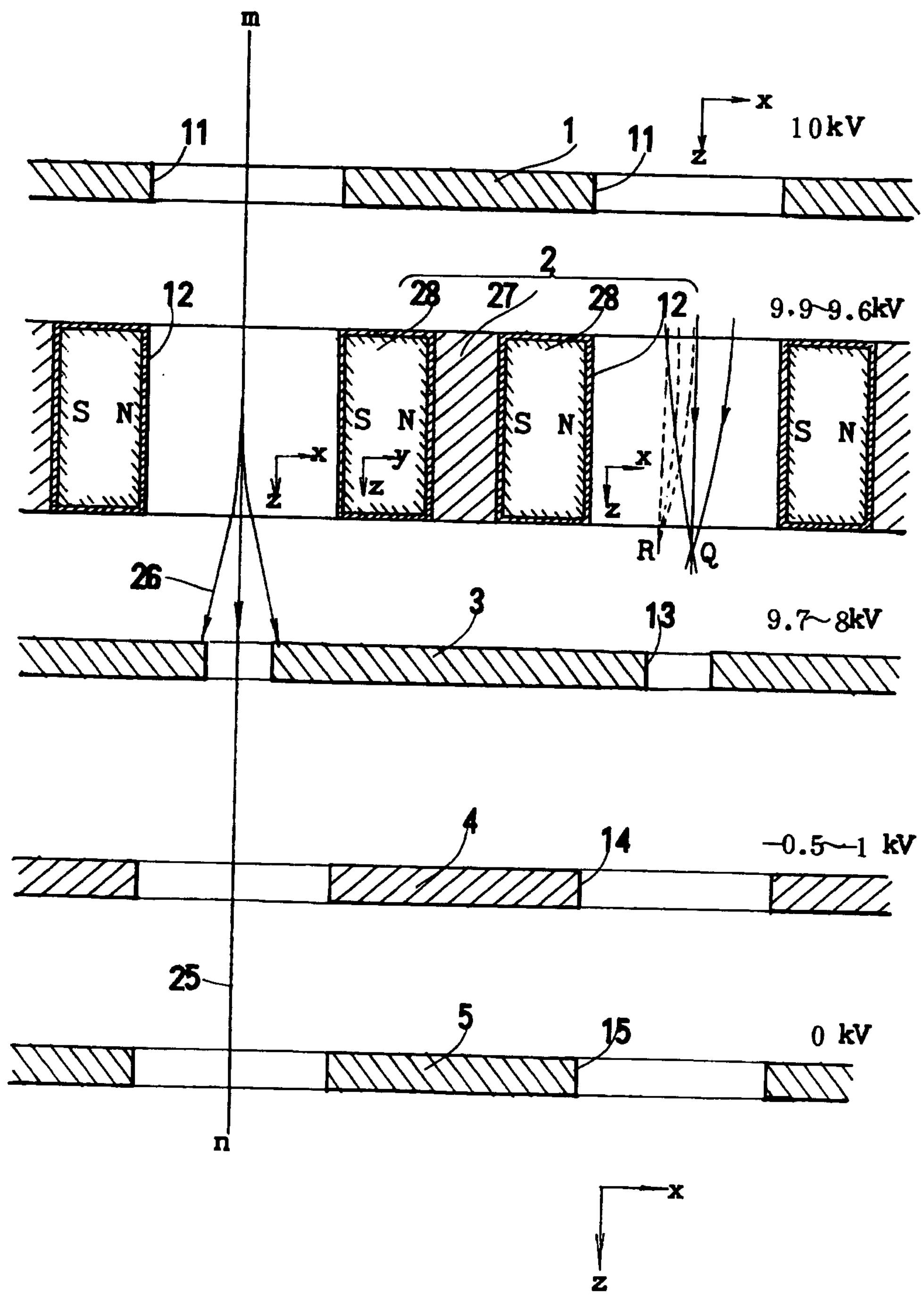

m
x
z
11
1
11
10kV
2
12
28
27
28
12
9.9~9.6kV
S N
S N
S N
S N
x
z
y
z
x
z
R
Q
26
3
13
9.7~8kV
4
14
-0.5~-1 kV
25
5
15
0 kV
n
x
z

FIG. 6

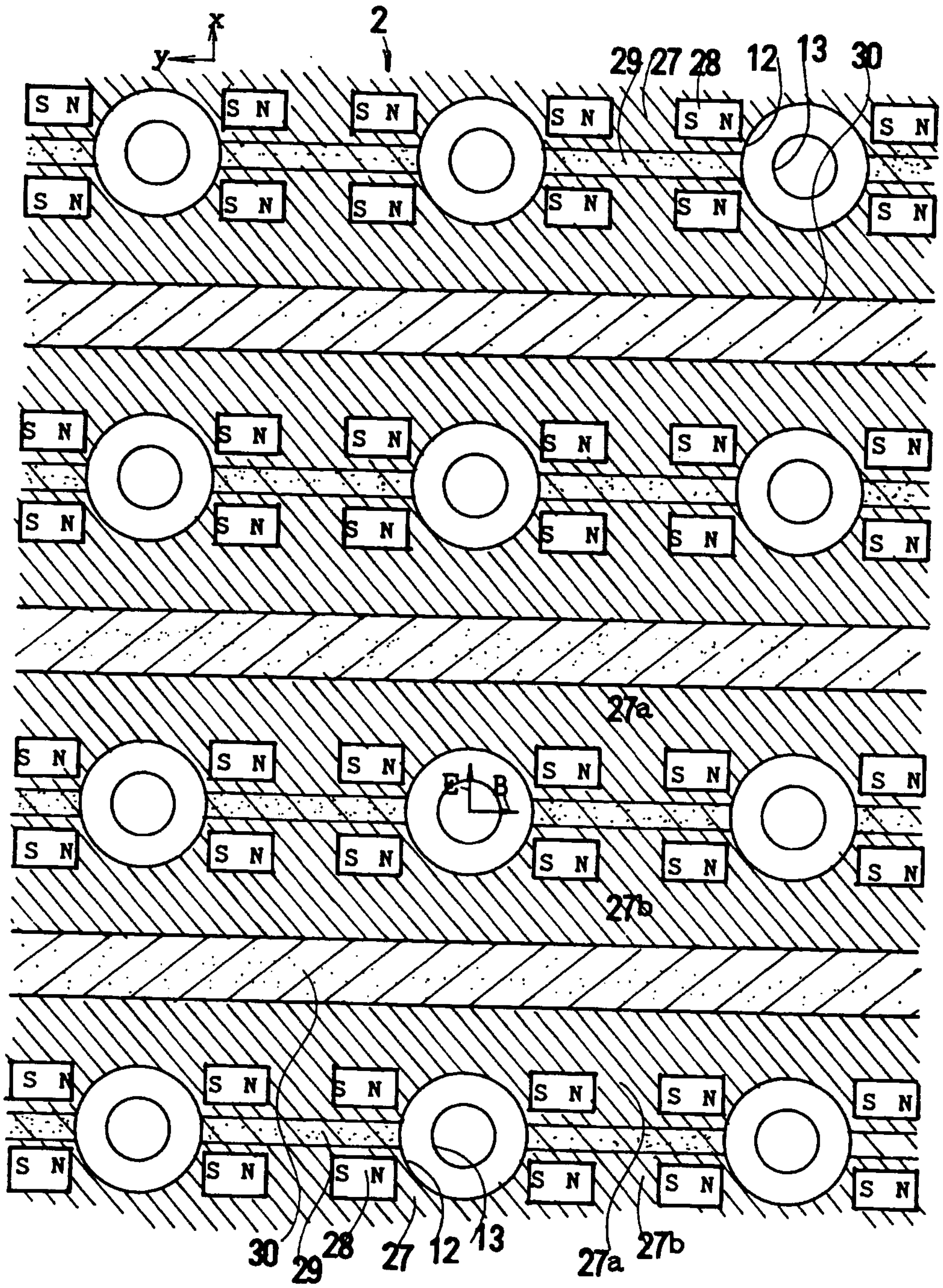


FIG. 7

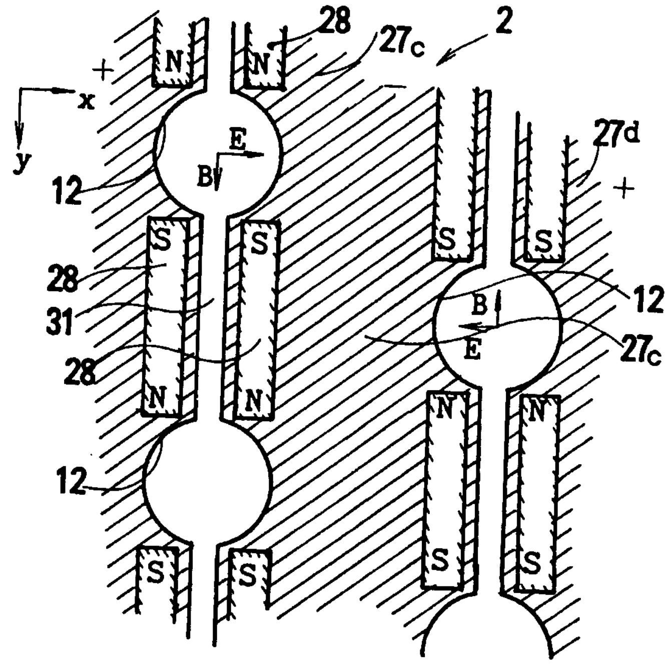

28
27c
2
+
x
y
N
N
E
B
12
27d
+
S
S
S
S
28
31
28
B
12
E
27c
N
N
N
N
12
S
S
S
S

FIG. 8

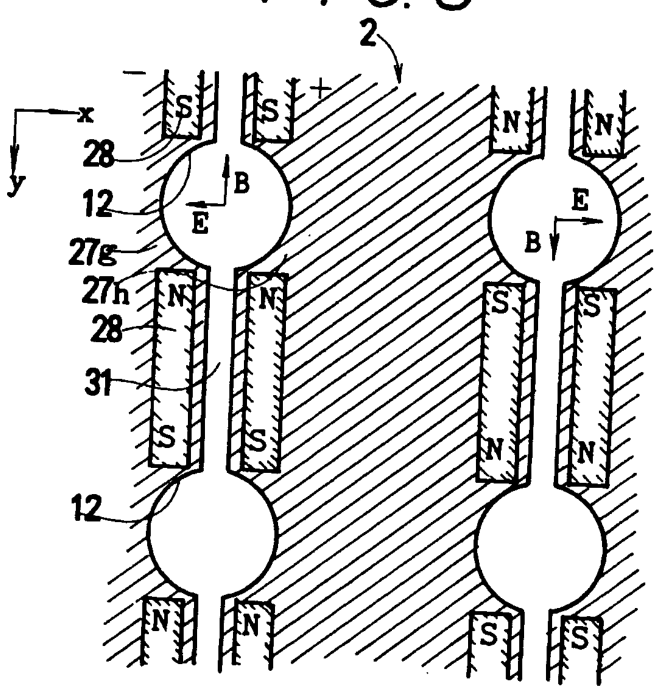
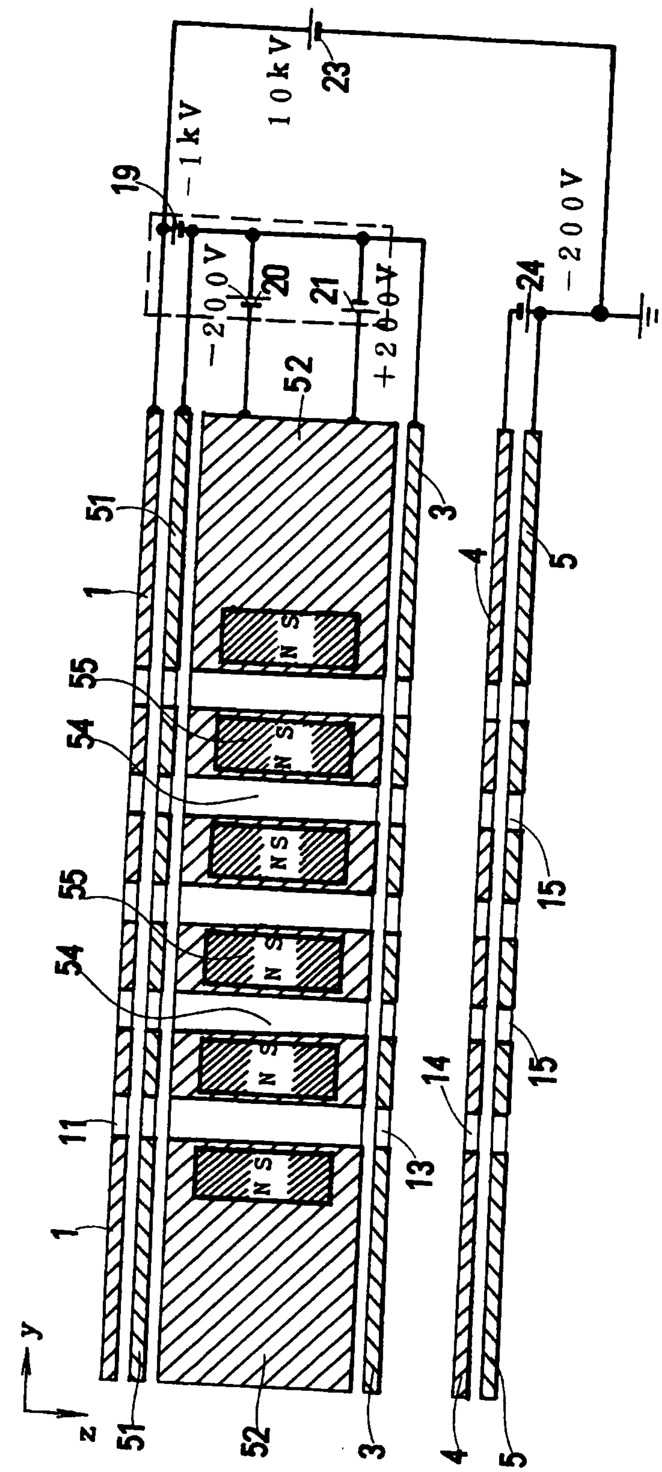

2
−
+
x
y
S
S
N
N
28
B
12
E
E
B
27g
27h
N
N
S
S
28
31
S
S
N
N
12
N
N
S
S

FIG.9



19
−1kV
10kV
23
20
21
−200V
+200V
24
−200V
52
51
1
55
54
11
13
14
15
3
4
5
N S
y
z

FIG. 10